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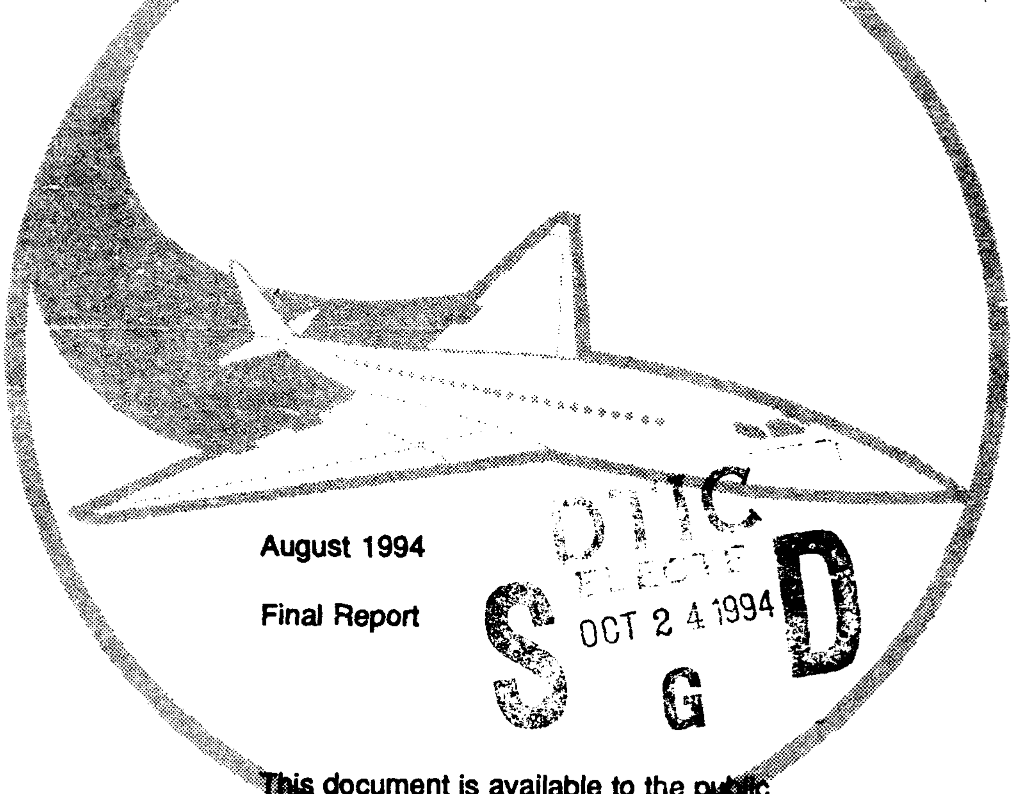
Marginal Aggregates in Flexible Pavements: Background Survey and Experimental Plan



August 1994

Final Report

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The US Army Engineer Waterways Experiment Station conducted this study as part of the Inter-Agency Agreement Project "Durability Criteria for Airport Pavements."

16. Abstract

The purpose of this study is to evaluate the utilization of substandard or marginal aggregates in flexible pavement construction of airport pavements. This investigation was undertaken to evaluate the effects of using lower quality aggregates such as rounded uncrushed gravels and sands on the rutting of flexible pavements. The scope of this research study included a review of available literature and existing data (Phase I), a laboratory evaluation organized to determine the effects of marginal aggregates and potential techniques to upgrade these substandard materials (Phase II), and a field evaluation involving test sections utilizing the most promising techniques (Phase III).

This report provides a review of existing data and literature concerning aggregate properties and their influence on the performance of base course materials and asphalt concrete mixtures. This report also discusses the experimental plan for this research study and provides a discussion and description of the state-of-the-art laboratory testing equipment that is being used to evaluate the engineering properties of the marginal aggregates. A summary and schedule of the remaining work has been included.

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PREFACE

This report was sponsored by the US Department of Transportation, Federal Aviation Administration (FAA) under Inter-Agency Agreement No. DTFA01-90-Z-02069, "Durability Criteria for Airport Pavements." The study was performed by the Pavement Systems Division (PSD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, during the period October 1990 to June 1993. Dr. A. McLaughlin was the FAA Technical Monitor.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL; Mr. H. H. Ulery, Jr., former Chief, PSD; and Dr. G. M. Hammitt II, Chief, PSD. This report was prepared under the direct supervision of Mr. T. W. Vollor, Chief, Materials Research and Construction Technology Branch, PSD. PSD personnel engaged in the laboratory testing included Messrs. Bill Burke, Jerry Duncan, Roosevelt Felix, Herbert McKnight, and Joey Simmons. The project's Principal Investigator was Mr. R. C. Ahlrich. This report was written by Mr. Ahlrich and Dr. R. S. Rollings.

The Director of WES during the preparation and publication of this report was Dr. Robert W. Whalin. The Commander and Deputy Director was COL Leonard G. Hassell, EN.

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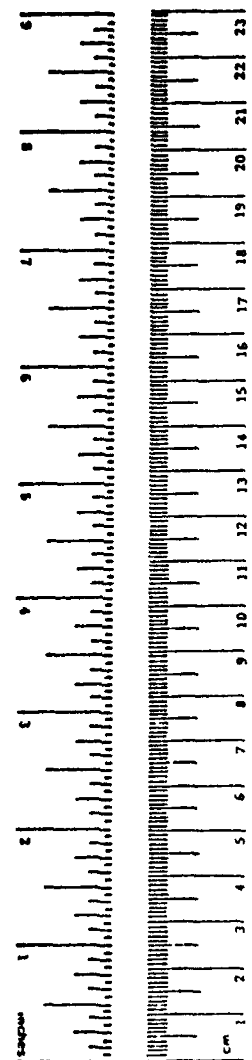
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

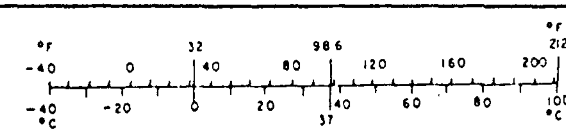
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

BACKGROUND

High quality aggregates are becoming increasingly scarce and expensive in many localities. Traditional flexible pavement specifications require high quality aggregates in the flexible pavement base course materials and asphalt concrete mixtures. In an increasing number of cases, locally available aggregates are not meeting applicable specifications, and aggregates that meet the specifications must be imported to the site at considerable expense[1].

The use of marginal aggregates in flexible pavement construction is one of the possible answers to high pavement construction costs and a lack of quality aggregate sources. A broad definition of a marginal aggregate is "any aggregate that is not normally usable because it does not have the characteristics required by the specification, but could be used successfully by modifying normal pavement design and construction procedures"[2]. For this study, marginal aggregates will be defined as aggregates that do not meet the Federal Aviation Administration's (FAA) specification requirements for airfield pavements.

Using local available marginal materials is often very tempting, but the decision to use or reject these materials should only be made after a complete evaluation. The decision should be based on an evaluation of the material characteristics and how these characteristics will affect the design, performance, and construction of the pavement. Potential problem areas must be clearly identified, or any expected cost savings will be lost[3].

Current FAA specifications were developed at times when high quality aggregates were readily available. However, this is no longer the case in many areas. This study will attempt to define in engineering terms the impact of using marginal aggregates in flexible pavements. Strategies for improving the performance of marginal aggregates to equal that of standard aggregates will be evaluated. The major emphasis will be on marginal aggregates for asphalt concrete mixtures.

PURPOSE

The purpose of the research study is to evaluate the utilization of marginal aggregates in flexible pavement construction for airfield pavements. Marginal aggregates have been defined as aggregates that do not meet FAA specification requirements. The current FAA guidance for airfield pavement construction is provided in FAA Advisory Circular AC-150/5370-10A, "Standards for Specifying Construction of Airports." Specific requirements are provided for asphalt pavements in Item P-401 (Plant Mix Bituminous Pavements) and for base courses in Item P-209 (Crushed Aggregate Base Course). Marginal aggregates can have one or more of the following deficiencies: improper gradation, lack of fractured faces, flat and elongated particles, high natural sand content, high LA abrasion and soundness values, excessive plasticity, and excessive amounts of No. 200 material. This research will determine if marginal aggregates can provide equivalent or acceptable pavement performance with an emphasis on pavement deformation and rutting.

SCOPE

This research study will be conducted in three phases. Phase I will be a review of available literature and existing data. Based on the literature review, Phase II, a laboratory study will be conducted using poor quality, less than acceptable aggregates that do not meet FAA requirements. The marginal aggregates will be compared to proven, accepted aggregates, to evaluate the effectiveness of these materials in flexible pavements. Various concepts including aggregate stabilization and asphalt modification along with other methods will be analyzed in the laboratory to determine the best approach when constructing flexible pavements with marginal aggregates. The final phase, Phase III, will take the concepts and techniques using marginal aggregates that have the greatest potential and evaluate these materials in field test sections. These field test sections will be trafficked with aircraft loads and tire pressures, monitored, and evaluated to determine the performance of the marginal aggregates.

After completing this research, guidance and recommendations for the use of marginal aggregates in flexible pavement construction for airfield pavements will be provided. This interim report documents Phase I. The laboratory study, Phase II, will be documented in Interim Report II. The construction and trafficking of the field test sections (Phase III) will be documented along with recommendations concerning marginal aggregates in the final technical report.

EFFECTS OF AGGREGATE PROPERTIES ON ASPHALT MIXTURES

The use of marginal aggregates in asphalt concrete mixtures is very attractive because these materials are generally more economical and readily available. The disadvantage of using these aggregates is that these materials can produce low quality asphalt concrete mixtures that have unsatisfactory pavement performance. Most marginal aggregates have material characteristics that produce pavements with low strength values[3,4].

Much research has been conducted concerning the effects of aggregate properties and characteristics on the quality and performance of asphalt concrete mixtures. A review of this research has been conducted and summarized into general categories that best relate to marginal aggregates as defined by the FAA. The literature review has been divided into the following areas: (1) gradation, (2) shape and surface texture, (3) aggregate quality, (4) material and mixture tests, and (5) field performance.

GRADATION

Elliot, Ford, Ghanim and Tu[5] conducted an investigation to evaluate the effect of variations in the gradation of aggregates on the properties of asphalt concrete mixtures. The primary objectives were to determine the effect of gradation variation on (1) creep behavior as a measure of rutting resistance, (2) split tensile strength as an indicator of fatigue resistance potential, (3) Marshall mix properties as a measure of mix acceptability and (4) resilient modulus as a design parameter.

From this investigation, the authors concluded the following:

a) Gradation variations have the greatest effect when gradation changes in the general shape of the gradation curve (fine to coarse or coarse to fine).

b) Coarse to fine gradation variations produce the highest Marshall flow while fine to coarse gradation variation produced the lowest Marshall flow.

c) Creep stiffness is lowest for coarse to fine and fine to coarse gradation variations.

d) Marshall stability is affected by gradation variations, fine gradations produce highest stability and fine to coarse gradations produce the lowest stability.

e) Coarse gradation variations produce the lowest tensile strengths.

Marker[6] concluded that particle shape and the amount of material passing the No. 4 sieve were major factors contributing to the tenderness of an asphalt concrete mixture. He discovered that most tender pavements have an excess of middle-sized sand particles in the aggregate gradation. This excess of mid-sized sand particles is revealed as a hump in the curve when the gradation is plotted as percent passing versus the sieve size raised to the 0.45 power (Fuller curve). Tenderness is generally most critical when this hump is near the No. 30 sieve. This condition is generally accompanied by a relatively low amount of minus No. 200 material. Marker also stated that rounded, uncrushed aggregates are more likely to contribute to tender mixtures, especially as the amount of uncrushed material passing the No. 4 sieve increases.

Moore and Welke[8] conducted numerous asphalt mix designs to determine the effect of fine aggregate. They stated that the asphalt concrete mixture gradation and aggregate angularity were very significant in increasing the stability of the mixtures. They reported that as the mixture gradation approached the Fuller curve for maximum density, the Marshall stability increased. They also stated that the more angular the fine aggregate, the higher the stability. The study concluded that rounded fine aggregates (natural sands) produced lower stabilities than crushed fine aggregates.

Brown[9] conducted a laboratory study to determine the relationship between asphalt mixture properties and maximum aggregate size. The laboratory testing procedures were chosen to analyze the effects of varying the size of the largest aggregate in a gradation. The tests used to evaluate the various mixtures included Marshall stability and flow, indirect tensile, static creep and resilient modulus. The laboratory evaluation provided the following conclusions: (1) no connection between stability and rutting resistance, (2) poor relationship between Marshall stability and the maximum aggregate size, (3) very little change in indirect tensile strength as maximum aggregate size changed, (4) creep test indicated an increased aggregate size would be more resistant to permanent deformation, and (5) the resilient modulus indicated good correlation with maximum aggregate size (i.e., the resilient modulus value increased as the maximum aggregate size increased).

Brown, McRae and Crawley[10] gathered information from various laboratory and field studies to discuss the effect of mineral filler, maximum aggregate size, aggregate gradation, crushed particles and stripping tendencies on the performance of asphalt concrete. The authors concluded that the quality and amount of filler greatly affected the asphalt concrete performance. They also concluded that additional minus No. 200 material produced a lower optimum asphalt content, a higher stability and a very sensitive asphalt mixture. Furthermore, some filler is required for stability, but an excessive amount (greater than 6 percent) produced unsatisfactory mixtures. The authors also stated that the maximum aggregate size greatly affected the pavement performance and that larger maximum aggregate sizes produce higher stability, better skid resistance, and lower optimum asphalt contents. The authors also stated that uncrushed aggregates such as sands and gravels produce mixtures with lower stability and decreased pavement performance.

SHAPE AND SURFACE TEXTURE

Herrin and Goetz[11] conducted a laboratory evaluation to determine the effect of aggregate shape on the stability of asphalt concrete mixtures. This laboratory study involved crushed and uncrushed gravel, crushed limestone for the coarse aggregate, and natural sand and crushed limestone sand for the fine aggregate. In their tests, the strength of the mixture, regardless of the type of coarse aggregate, increased substantially when the fine aggregate was changed from rounded sand to crushed limestone. A major finding was that the strength of the asphalt mixture was affected more by a change in the fine aggregate than a change in the coarse aggregate.

Wedding and Gaynor[12] evaluated the effect of particle shape in dense graded asphalt concrete mixtures. The percentages of crushed and uncrushed coarse aggregates and the types of fine aggregate which included natural and washed concrete sands were varied in the mixtures. The analysis of the different aggregate blends was conducted on specimens produced by the Marshall procedure. The authors reached the following conclusions from this study.

a) Asphalt mixtures with crushed particles produced higher stability values than mixtures with uncrushed, rounded aggregates.

b) The substitution of crushed gravel sand in place of natural sand increased the stability of the mixtures equivalent to the increase of adding 25 percent crushed coarse aggregate.

c) The substitution of all crushed aggregate for natural sand and gravel increased the stability approximately 45 percent.

d) An increase in the amount of crushed particles caused a decrease in unit weight, and an increase in voids in mineral aggregate and optimum asphalt content.

Griffith and Kallas[13,14] conducted several laboratory evaluations that determined the effects of aggregate characteristics on asphalt mixtures. They studied the effect of aggregate type on voids and strength characteristics of asphalt concrete mixtures. The authors found that uncrushed gravel mixtures develop voids lower than the voids in crushed gravel mixtures at optimum asphalt contents. They also evaluated the influence of fine aggregates on the strength of asphalt concrete specimens. Various combinations of aggregate gradations using natural and crushed coarse aggregate and natural sand fine aggregate were analyzed. They found that an increase in angularity or crushed fines increased the Marshall and Hveem stability values at the optimum asphalt content. An increase in angularity in the fine aggregate also increased the minimum void percentages and increased the optimum asphalt contents.

Field[15] conducted a study to determine the effect of variation of crushed aggregate percentages in asphalt concrete mixtures. He found that replacing uncrushed aggregates with crushed aggregates increased the stability and increased the void content and voids in mineral aggregate for a given asphalt content. The higher VMA values allow more asphalt in the mix which improves the durability of the asphalt concrete pavement.

Gaudette and Welke[16] conducted a laboratory study that determined the effect of crushed faces on the stability of asphalt concrete mixtures. The authors evaluated the relationship between the number of crushed faces on coarse aggregate to stability and the percentage of crushed aggregate to stability. They concluded that the stability of the mixture increased significantly when the percentage crushed aggregates was increased from 0 to 50 percent. The number of crushed or fractured faces, whether it was 2, 3 or more, had no added effect on the stability when less than 50 percent crushed aggregate was used. Above 50 percent crushed aggregate, the aggregates with three or more fractured faces produced mixtures with increasing stability while the stability for mixtures with two or less fractured faces tended to level off.

Maupin[17] conducted a laboratory study to evaluate the effect of particle shape and surface texture on the fatigue behavior of asphalt concrete. The study used three different particle shapes, round, subangular, and angular. Asphalt concrete mixtures were produced with uncrushed gravel (round), limestone (subangular), and slabby slate (angular). Beam specimens were prepared and tested with constant strain fatigue. The laboratory study concluded that rounded gravel mixture had a longer fatigue life than the other mixtures.

Shklarsky and Livneh[18] conducted a laboratory study involving sands and gravels. They evaluated the difference between uncrushed and crushed coarse aggregate combined with natural sand and crushed fine aggregate. The authors found that replacing natural sand materials with crushed fine aggregate increased the stability and strength properties of Marshall specimens, reduced permanent deformation, improved resistance to wear, reduced asphalt content sensitivity, and increased voids. They also concluded that replacing uncrushed coarse aggregate with crushed coarse aggregate did not significantly improve the asphalt concrete mixture.

Kalcheff and Tunnicliff[19] conducted a laboratory study to determine the effects of crushed aggregate size and shape on properties of asphalt concrete mixtures. They specifically evaluated the effect of coarse aggregate gradations, shape effects of fine aggregates, and effects of high mineral filler content. The laboratory specimens were produced with Marshall and Hveem methods using aggregate blends composed of natural and manufactured sands. The optimum asphalt content was approximately the same for natural sand mixtures and manufactured sand mixtures if the sands had similar particle shape. The optimum asphalt content was higher if the manufactured sand had more angular particles. The authors found that asphalt concrete mixtures containing crushed fine aggregate were more resistant to permanent deformation from repeated loadings than comparable mixtures containing natural sand (Figure 1). The behavior of the asphalt concrete mixture was improved when manufactured sands replaced natural sands.

Lottman and Goetz[20] evaluated the effect of crushed gravel fine aggregate on the strength of asphalt mixtures. The authors found that the strength of asphalt mixtures was increased when mixtures contained crushed gravel fine aggregate instead of natural sand fine aggregates. They stated that the increase in strength was attributed to the angularity and the roughness of the crushed fine aggregate. The authors recommended that some amount of crushed fine aggregate be used with natural sands in asphalt mixtures to produce sufficient stability for high quality pavements.

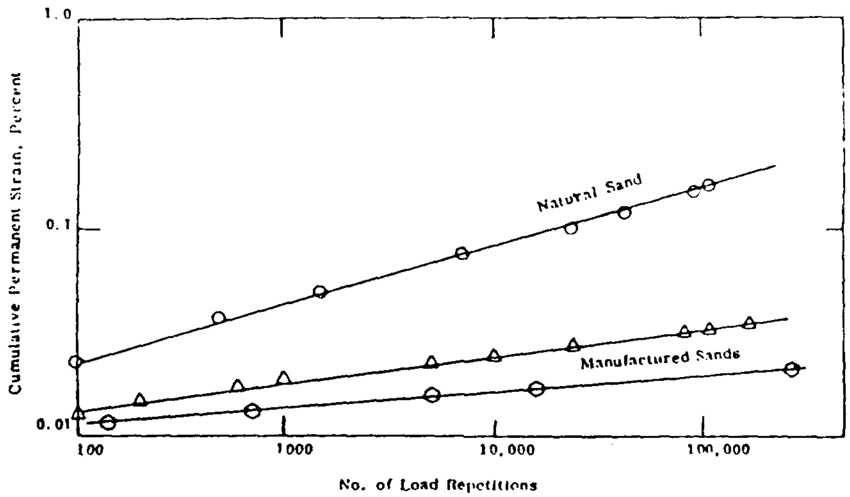

Figure 1. Typical relationship between permanent deformation and type of sand[19]

Button and Perdomo[21] conducted a study to evaluate the effects of natural sands on permanent deformation and to quantify the influence on resistance to plastic deformation when natural sand is replaced with crushed fine aggregate. The study showed that total deformation and rate of deformation increased as the percentage of natural sand increased (Figure 2). The texture, shape, and porosity of the fine aggregate were major factors controlling plastic deformation in asphalt concrete mixtures. The authors recommended replacing natural sand material with manufactured sand to increase the resistance of the asphalt concrete pavement to permanent deformation.

Kandhal and Wegner[22] conducted a study to determine the effect of crushed aggregate on properties of asphalt concrete for the Pennsylvania Department of Transportation. They found that replacing natural sand with crushed sand improved the Marshall stability and reduced permanent deformation. The authors also concluded that replacing uncrushed coarse aggregate with crushed coarse material did not significantly improve the asphalt mix properties.

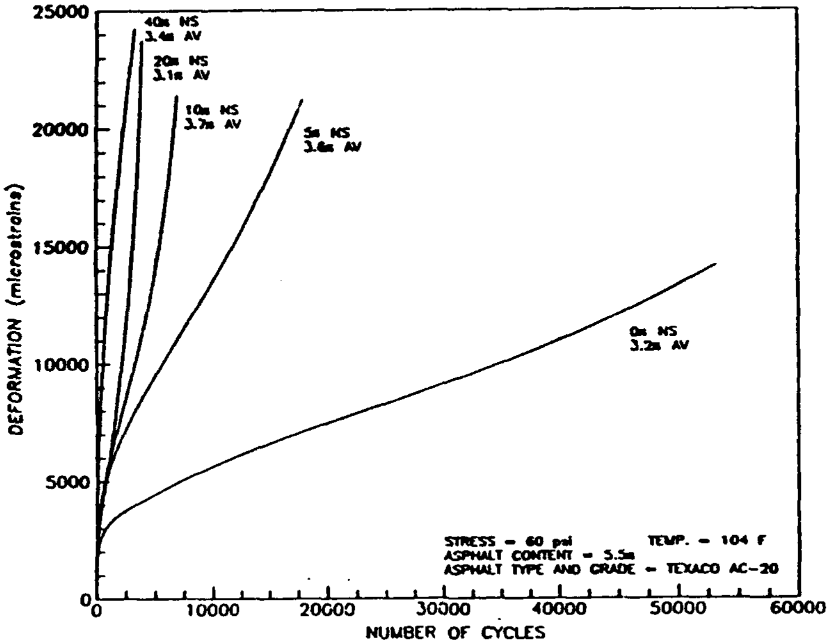

Figure 2. Relationship between pavement deformation and natural sand content[21]

Ahlrich[23] conducted a laboratory study to determine the influence of various amounts of natural sands on the engineering properties of asphalt concrete mixtures and to set quantitative limits of natural sand to prevent unstable mixtures and reduce rutting potential. The study indicated that the use of natural sand materials decreased the stability and strength characteristics of asphalt concrete mixtures and that replacing natural sand materials with crushed sand materials increased the resistance to permanent deformation. The author concluded that to maximize the reduction in rutting potential for heavy duty pavements (airports), all aggregates should be crushed. He also stated that if natural sands were to be used, a maximum limit of 15 percent by weight should be specified.

AGGREGATE QUALITY

Amirkhanian, Kaczmarek, and Burati[24] conducted a laboratory study to investigate the effects of LA abrasion values on the strength of asphalt concrete mixtures. Laboratory specimens were prepared according to the Marshall procedure to evaluate high and low LA abrasion values and degradation of extracted aggregates. The Marshall specimen were tested using the resilient modulus and indirect tensile tests on dry and conditioned specimen. The authors concluded that there was not a significant difference in resilient modulus and indirect tensile test results when comparing high LA abrasion values to low LA abrasion values. They also concluded that degradation of aggregates with high LA abrasion values was not significant when compared to low LA abrasion values.

Rollings[3] and Dolar-Mantuani[25] reported that the sulfate soundness test is used in many specifications but that it does not always accurately predict performance. They reported that the sulfate soundness test cannot clearly discriminate between aggregates that are susceptible to freezing and thawing and those that are not.

Rollings[3] stated that cohesive fines in aggregates were detrimental to the pavement's performance. Silt and clay sized particles are generally not allowed or limited in conventional asphalt aggregates to eliminate some construction, durability, and stability problems. These fine aggregates usually require extra asphalt for binder and extra effort to process before using in asphalt mixtures.

Brown and Graham[26] conducted a laboratory study to evaluate the relative benefits of using loess filler in sand asphalt mixtures. This study was conducted because results from the U.S. Army Corps of Engineers New Orleans District had shown that asphalt mixtures with loess material were more impervious to water than other mixtures. This study concluded that loess filler did improve the stability, tensile strength, and water susceptibility of sand mixtures. Although the loess material did improve the sand mixtures, conventional limestone dust filler produced better asphalt mixtures. The authors concluded that loess filler could be used to improve sand asphalt mixtures if limestone dust was not available.

MATERIAL AND MIXTURE TESTS

Boutilier[27] conducted a laboratory study to determine the relationship between the Particle Index developed by Huang[28] and the properties of asphalt concrete mixtures. The Particle Index is a function of the aggregate shape, texture, and angularity. This value is larger for aggregates that are more irregular, angular and rougher. The study indicated that there was a definite relationship between the Particle Index values and the properties of asphalt concrete mixtures. Figure 3 illustrates the relationship between Particle Index and Marshall stability and flow.

McLeod and Davidson[29] also conducted an extensive laboratory study to determine the relationship between Particle Index and asphalt concrete mixtures. The authors concluded that aggregates with rounded particles and smooth surface textures have a particle index of 6 or 7 or less, while aggregates with highly crushed angular particles have a particle index of 15 to 20 or more. They illustrated a distinct relationship between particle index and Marshall stability in Figure 4. They also concluded that the particle index of fine aggregate has a greater influence than the particle index of coarse aggregate on Marshall stability.

Meir and Elnicky[30] conducted a laboratory study to evaluate various test methods that provide information about the shape and surface texture of fine aggregates for asphalt mixtures and relate these properties to asphalt concrete properties. The authors concluded that the shape and surface texture of fine aggregate can be evaluated by a number of tests. These tests include the National Crush Stone Association procedure, Particle Index method, Rex and Peck Tim Index, and the void ratio method of Western Technologies. The direct shear test did not produce acceptable results.

Kandhal, Motter, and Khatri[31] conducted a laboratory study to quantify the particle shape and texture of various natural and manufactured sands using the Particle Index test, and the National Aggregate Association's (NAA) Methods A and B. They concluded that a Particle Index value of 14 seems to be the division between natural and manufactured sands. The NAA Methods A and B also divide the natural and manufactured sands with void contents of 44.5 and 48.3 respectively.

Winford[32] conducted a laboratory study to quantify particle characteristics and to evaluate relationships between these characteristics and permanent deformation and to recommend a test method for particle characterization. He concluded that the angle of internal friction derived from the direct shear test provides a reliable partition between natural and manufactured sands. He also concluded that a composite Particle Index value of 14 was the separation between natural and manufactured sands. NAA Methods A and B also correlated very well with the Particle Index test. He determined that the direct shear test was the simplest, quickest, and cheapest method for determining fine aggregate angularity and surface texture. The author also developed several relationships between the percentage of crushed aggregates and permanent strain or deformation. A relationship for uncrushed coarse aggregate and crushed fine aggregate is shown in Figure 5.

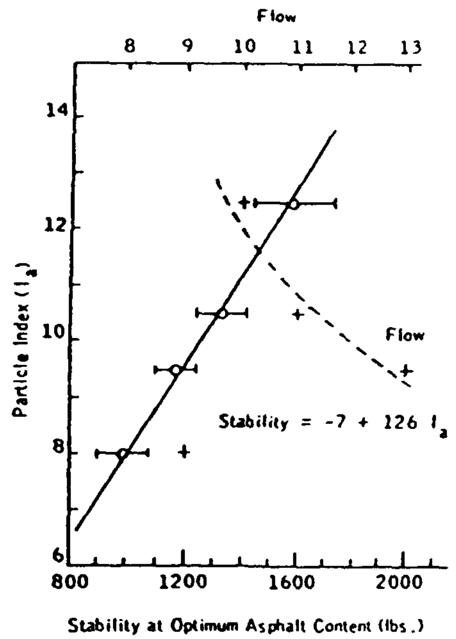

Figure 3. Relationship between Particle Index and Marshall stability and flow[27]

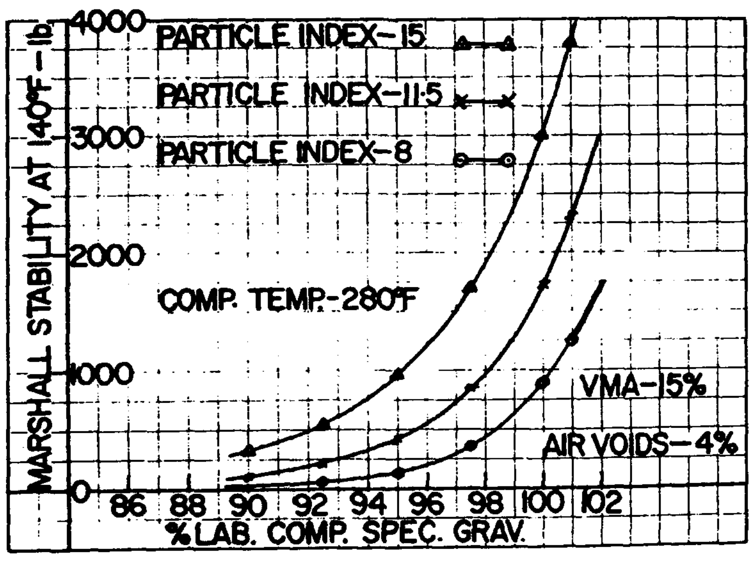

Figure 4. Relationship between Marshall stability and increasing Particle Index values[29]

Marks, Monroe, and Adam[33] conducted a laboratory evaluation that analyzed the effects of crushed particles in asphalt concrete mixtures. The laboratory tests included Marshall stability, indirect tensile, resilient modulus, and creep tests. Results of the study indicated the stability values increased substantially as the percentage of crushed aggregate increased. The resilient modulus data did not correlate with the percent of crushed particles or indicate resistance to rutting. Data from the creep test indicated rutting potential was very dependent on the percent of crushed aggregate (Figure 6).

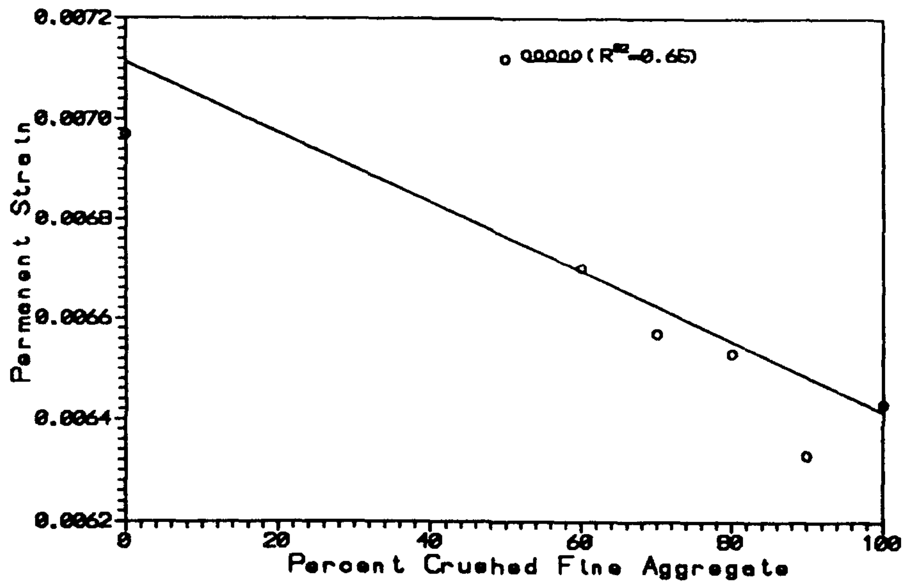

Figure 5. Pavement deformation of uncrushed coarse aggregate mixtures versus percent crushed fine aggregate[32]

Ahlrich[23] found that the amount of natural sand did affect the results of the indirect tensile, resilient modulus and unconfined creep-rebound tests. The indirect tensile results indicated a reduction in mixture strength as the percentage of natural sand increased. The resilient modulus test results were very inconsistent and provided no discernable trend. The unconfined creep-rebound test results indicated a strong relationship between the percentage of natural sand and rutting potential. The axial and permanent deformation values increased significantly as the natural sand content increased. The creep modulus value decreased significantly as the percentage of natural sand increased.

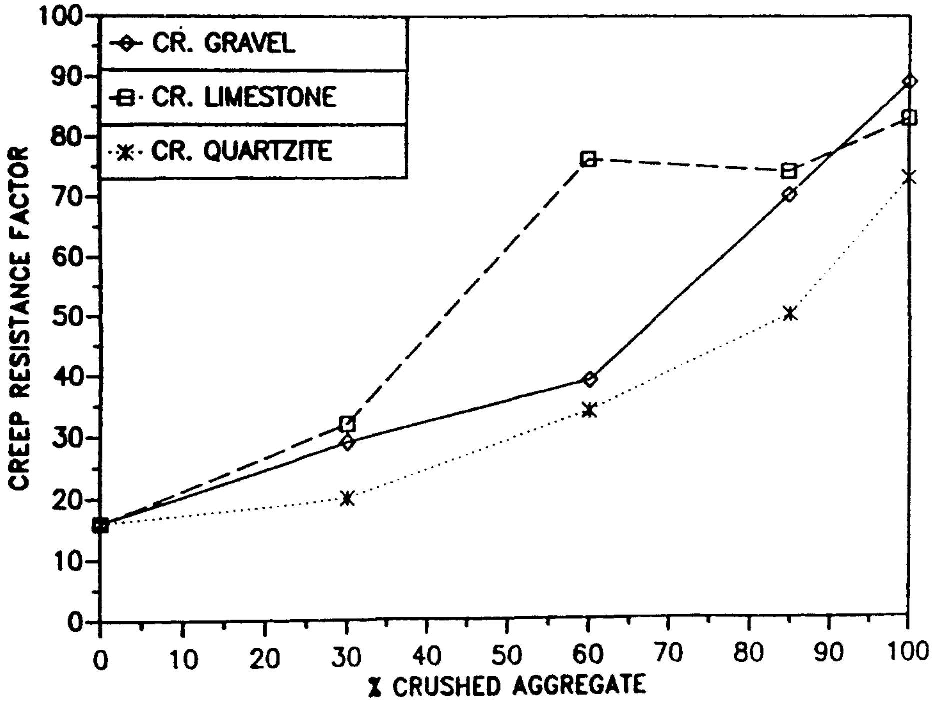

Figure 6. Relationship between creep resistance factor and percent crushed aggregate[33]

FIELD PERFORMANCE

Foster[34] evaluated the effect of fine aggregate on the strength of dense-graded asphalt concrete mixtures in field test sections at the U.S. Army Engineer Waterways Experiment Station (WES). The study involved constructing and trafficking field test sections constructed with three asphalt mixtures, a sand asphalt mix and two coarse aggregate mixtures containing the same fine aggregate. Based on the pavement's performance after trafficking, the author concluded that the true capacity to resist traffic induced stresses is controlled by the characteristics of the fine aggregate. These results agreed with findings from earlier tests at WES that were conducted during the development of the Marshall procedure[35].

Grau[4] evaluated the effects of natural sands and fine aggregates in field test sections. This study demonstrated that increases in amounts of natural sand and finer sand gradations produced less stable mixtures. A significant decrease in stability occurred when uncrushed gravel and natural sand were used together. The stability values of asphalt concrete mixtures increased significantly when crushed sand was used in place of natural sand.

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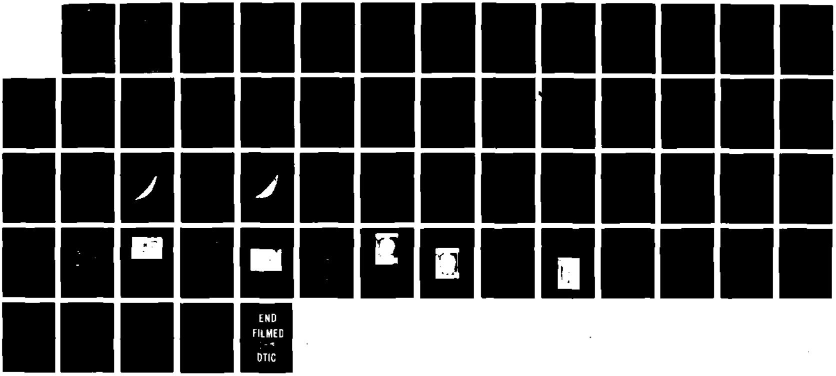

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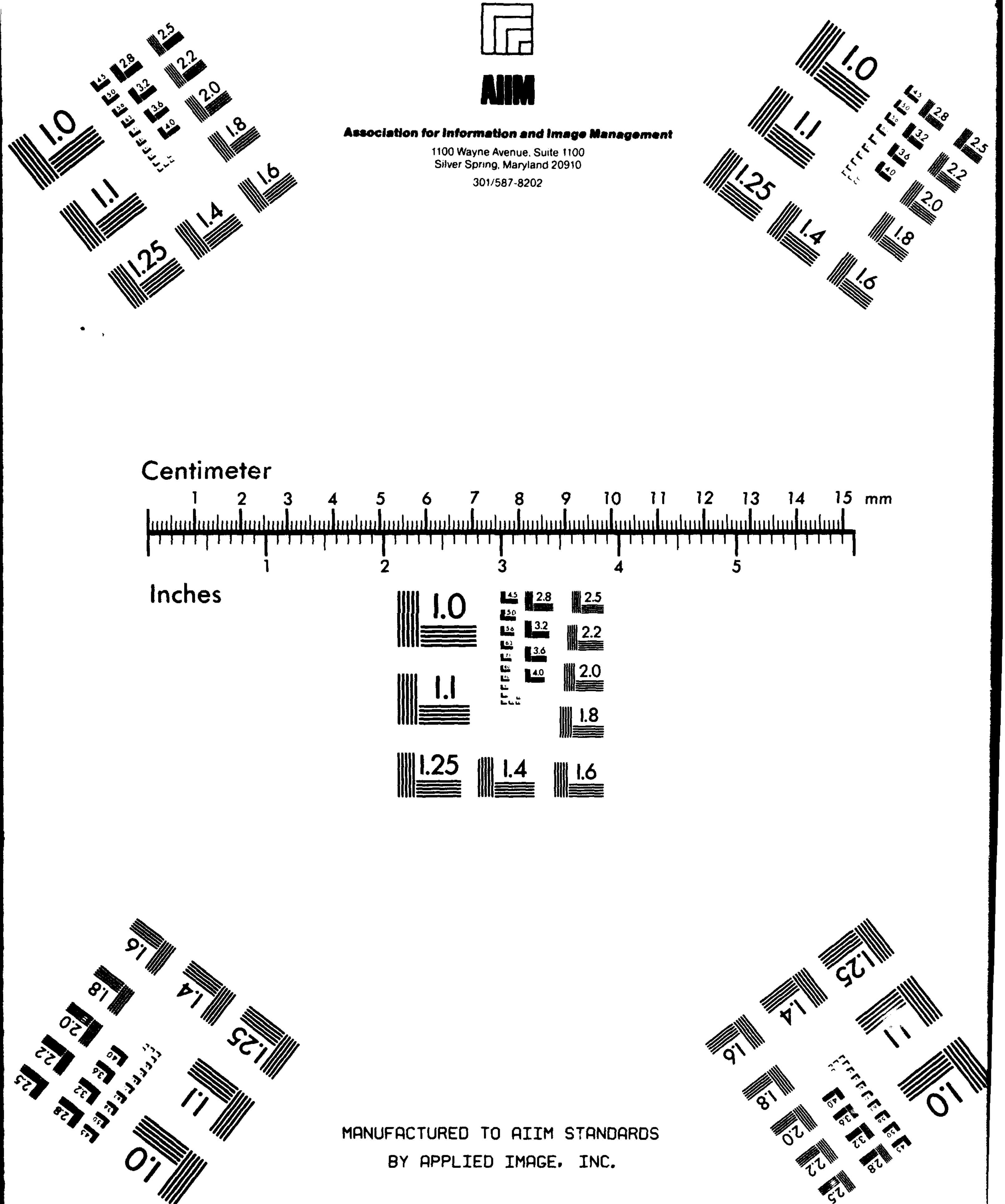

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Marginal Aggregates in Flexible Pavements: Background Survey and Experimental Plan

August 1994

Final Report

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The US Army Engineer Waterways Experiment Station conducted this study as part of the Inter-Agency Agreement Project "Durability Criteria for Airport Pavements."

16. Abstract

The purpose of this study is to evaluate the utilization of substandard or marginal aggregates in flexible pavement construction of airport pavements. This investigation was undertaken to evaluate the effects of using lower quality aggregates such as rounded uncrushed gravels and sands on the rutting of flexible pavements. The scope of this research study included a review of available literature and existing data (Phase I), a laboratory evaluation organized to determine the effects of marginal aggregates and potential techniques to upgrade these substandard materials (Phase II), and a field evaluation involving test sections utilizing the most promising techniques (Phase III).

This report provides a review of existing data and literature concerning aggregate properties and their influence on the performance of base course materials and asphalt concrete mixtures. This report also discusses the experimental plan for this research study and provides a discussion and description of the state-of-the-art laboratory testing equipment that is being used to evaluate the engineering properties of the marginal aggregates. A summary and schedule of the remaining work has been included.

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PREFACE

This report was sponsored by the US Department of Transportation, Federal Aviation Administration (FAA) under Inter-Agency Agreement No. DTFA01-90-Z-02069, "Durability Criteria for Airport Pavements." The study was performed by the Pavement Systems Division (PSD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, during the period October 1990 to June 1993. Dr. A. McLaughlin was the FAA Technical Monitor.

This study was conducted under the general supervision of Dr. W. F. Marcuson III, Chief, GL; Mr. H. H. Ulery, Jr., former Chief, PSD; and Dr. G. M. Hammitt II, Chief, PSD. This report was prepared under the direct supervision of Mr. T. W. Vollor, Chief, Materials Research and Construction Technology Branch, PSD. PSD personnel engaged in the laboratory testing included Messrs. Bill Burke, Jo[illegible] Duncan, Roosevelt Felix, Herbert McKnight, and Joey Simmons. The projec[illegible]ncipal Investigator was Mr. R. C. Ahlrich. This report was written by Mr [illegible]ch and Dr. R. S. Rollings.

The Director of WES during the preparation and publication of this report was Dr. Robert W. Whalin. The Commander and Deputy Director was COL Leonard G. Hassell, EN.

METRIC CONVERSION FACTORS

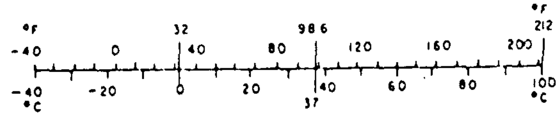
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

BACKGROUND

High quality aggregates are becoming increasingly scarce and expensive in many localities. Traditional flexible pavement specifications require high quality aggregates in the flexible pavement base course materials and asphalt concrete mixtures. In an increasing number of cases, locally available aggregates are not meeting applicable specifications, and aggregates that meet the specifications must be imported to the site at considerable expense[1].

The use of marginal aggregates in flexible pavement construction is one of the possible answers to high pavement construction costs and a lack of quality aggregate sources. A broad definition of a marginal aggregate is "any aggregate that is not normally usable because it does not have the characteristics required by the specification, but could be used successfully by modifying normal pavement design and construction procedures"[2]. For this study, marginal aggregates will be defined as aggregates that do not meet the Federal Aviation Administration's (FAA) specification requirements for airfield pavements.

Using local available marginal materials is often very tempting, but the decision to use or reject these materials should only be made after a complete evaluation. The decision should be based on an evaluation of the material characteristics and how these characteristics will affect the design, performance, and construction of the pavement. Potential problem areas must be clearly identified, or any expected cost savings will be lost[3].

Current FAA specifications were developed at times when high quality aggregates were readily available. However, this is no longer the case in many areas. This study will attempt to define in engineering terms the impact of using marginal aggregates in flexible pavements. Strategies for improving the performance of marginal aggregates to equal that of standard aggregates will be evaluated. The major emphasis will be on marginal aggregates for asphalt concrete mixtures.

PURPOSE

The purpose of the research study is to evaluate the utilization of marginal aggregates in flexible pavement construction for airfield pavements. Marginal aggregates have been defined as aggregates that do not meet FAA specification requirements. The current FAA guidance for airfield pavement construction is provided in FAA Advisory Circular AC-150/5370-10A, "Standards for Specifying Construction of Airports." Specific requirements are provided for asphalt pavements in Item P-401 (Plant Mix Bituminous Pavements) and for base courses in Item P-209 (Crushed Aggregate Base Course). Marginal aggregates can have one or more of the following deficiencies: improper gradation, lack of fractured faces, flat and elongated particles, high natural sand content, high LA abrasion and soundness values, excessive plasticity, and excessive amounts of No. 200 material. This research will determine if marginal aggregates can provide equivalent or acceptable pavement performance with an emphasis on pavement deformation and rutting.

SCOPE

This research study will be conducted in three phases. Phase I will be a review of available literature and existing data. Based on the literature review, Phase II, a laboratory study will be conducted using poor quality, less than acceptable aggregates that do not meet FAA requirements. The marginal aggregates will be compared to proven, accepted aggregates, to evaluate the effectiveness of these materials in flexible pavements. Various concepts including aggregate stabilization and asphalt modification along with other methods will be analyzed in the laboratory to determine the best approach when constructing flexible pavements with marginal aggregates. The final phase, Phase III, will take the concepts and techniques using marginal aggregates that have the greatest potential and evaluate these materials in field test sections. These field test sections will be trafficked with aircraft loads and tire pressures, monitored, and evaluated to determine the performance of the marginal aggregates.

After completing this research, guidance and recommendations for the use of marginal aggregates in flexible pavement construction for airfield pavements will be provided. This interim report documents Phase I. The laboratory study, Phase II, will be documented in Interim Report II. The construction and trafficking of the field test sections (Phase III) will be documented along with recommendations concerning marginal aggregates in the final technical report.

EFFECTS OF AGGREGATE PROPERTIES ON ASPHALT MIXTURES

The use of marginal aggregates in asphalt concrete mixtures is very attractive because these materials are generally more economical and readily available. The disadvantage of using these aggregates is that these materials can produce low quality asphalt concrete mixtures that have unsatisfactory pavement performance. Most marginal aggregates have material characteristics that produce pavements with low strength values[3,4].

Much research has been conducted concerning the effects of aggregate properties and characteristics on the quality and performance of asphalt concrete mixtures. A review of this research has been conducted and summarized into general categories that best relate to marginal aggregates as defined by the FAA. The literature review has been divided into the following areas: (1) gradation, (2) shape and surface texture, (3) aggregate quality, (4) material and mixture tests, and (5) field performance.

GRADATION

Elliot, Ford, Ghanim and Tu[5] conducted an investigation to evaluate the effect of variations in the gradation of aggregates on the properties of asphalt concrete mixtures. The primary objectives were to determine the effect of gradation variation on (1) creep behavior as a measure of rutting resistance, (2) split tensile strength as an indicator of fatigue resistance potential, (3) Marshall mix properties as a measure of mix acceptability and (4) resilient modulus as a design parameter.

From this investigation, the authors concluded the following:

a) Gradation variations have the greatest effect when gradation changes in the general shape of the gradation curve (fine to coarse or coarse to fine).

b) Coarse to fine gradation variations produce the highest Marshall flow while fine to coarse gradation variation produced the lowest Marshall flow.

c) Creep stiffness is lowest for coarse to fine and fine to coarse gradation variations.

d) Marshall stability is affected by gradation variations, fine gradations produce highest stability and fine to coarse gradations produce the lowest stability.

e) Coarse gradation variations produce the lowest tensile strengths.

Marker[6] concluded that particle shape and the amount of material passing the No. 4 sieve were major factors contributing to the tenderness of an asphalt concrete mixture. He discovered that most tender pavements have an excess of middle-sized sand particles in the aggregate gradation. This excess of mid-sized sand particles is revealed as a hump in the curve when the gradation is plotted as percent passing versus the sieve size raised to the 0.45 power (Fuller curve). Tenderness is generally most critical when this hump is near he No. 30 sieve. This condition is generally accompanied by a relatively low amount of minus No. 200 material. Marker also stated that rounded, uncrushed aggregates are more likely to contribute to tender mixtures, especially as the amount of uncrushed material passing the No. 4 sieve increases.

Moore and Welke[8] conducted numerous asphalt mix designs to determine the effect of fine aggregate. They stated that the asphalt concrete mixture gradation and aggregate angularity were very significant in increasing the stability of the mixtures. They reported that as the mixture gradation approached the Fuller curve for maximum density, the Marshall stability increased. They also stated that the more angular the fine aggregate, the higher the stability. The study concluded that rounded fine aggregates (natural sands) produced lower stabilities than crushed fine aggregates.

Brown[9] conducted a laboratory study to determine the relationship between asphalt mixture properties and maximum aggregate size. The laboratory testing procedures were chosen to analyze the effects of varying the size of the largest aggregate in a gradation. The tests used to evaluate the various mixtures included Marshall stability and flow, indirect tensile, static creep and resilient modulus. The laboratory evaluation provided the following conclusions: (1) no connection between stability and rutting resistance, (2) poor relationship between Marshall stability and the maximum aggregate size, (3) very little change in indirect tensile strength as maximum aggregate size changed, (4) creep test indicated an increased aggregate size would be more resistant to permanent deformation, and (5) the resilient modulus indicated good correlation with maximum aggregate size (i.e., the resilient modulus value increased as the maximum aggregate size increased).

Brown, McRae and Crawley[10] gathered information from various laboratory and field studies to discuss the effect of mineral filler, maximum aggregate size, aggregate gradation, crushed particles and stripping tendencies on the performance of asphalt concrete. The authors concluded that the quality and amount of filler greatly affected the asphalt concrete performance. They also concluded that additional minus No. 200 material produced a lower optimum asphalt content, a higher stability and a very sensitive asphalt mixture. Furthermore, some filler is required for stability, but an excessive amount (greater than 6 percent) produced unsatisfactory mixtures. The authors also stated that the maximum aggregate size greatly affected the pavement performance and that larger maximum aggregate sizes produce higher stability, better skid resistance, and lower optimum asphalt contents. The authors also stated that uncrushed aggregates such as sands and gravels produce mixtures with lower stability and decreased pavement performance.

SHAPE AND SURFACE TEXTURE

Herrin and Goetz[11] conducted a laboratory evaluation to determine the effect of aggregate shape on the stability of asphalt concrete mixtures. This laboratory study involved crushed and uncrushed gravel, crushed limestone for the coarse aggregate, and natural sand and crushed limestone sand for the fine aggregate. In their tests, the strength of the mixture, regardless of the type of coarse aggregate, increased substantially when the fine aggregate was changed from rounded sand to crushed limestone. A major finding was that the strength of the asphalt mixture was affected more by a change in the fine aggregate than a change in the coarse aggregate.

Wedding and Gaynor[12] evaluated the effect of particle shape in dense graded asphalt concrete mixtures. The percentages of crushed and uncrushed coarse aggregates and the types of fine aggregate which included natural and washed concrete sands were varied in the mixtures. The analysis of the different aggregate blends was conducted on specimens produced by the Marshall procedure. The authors reached the following conclusions from this study.

a) Asphalt mixtures with crushed particles produced higher stability values than mixtures with uncrushed, rounded aggregates.

b) The substitution of crushed gravel sand in place of natural sand increased the stability of the mixtures equivalent to the increase of adding 25 percent crushed coarse aggregate.

c) The substitution of all crushed aggregate for natural sand and gravel increased the stability approximately 45 percent.

d) An increase in the amount of crushed particles caused a decrease in unit weight, and an increase in voids in mineral aggregate and optimum asphalt content.

Griffith and Kallas[13,14] conducted several laboratory evaluations that determined the effects of aggregate characteristics on asphalt mixtures. They studied the effect of aggregate type on voids and strength characteristics of asphalt concrete mixtures. The authors found that uncrushed gravel mixtures develop voids lower than the voids in crushed gravel mixtures at optimum asphalt contents. They also evaluated the influence of fine aggregates on the strength of asphalt concrete specimens. Various combinations of aggregate gradations using natural and crushed coarse aggregate and natural sand fine aggregate were analyzed. They found that an increase in angularity or crushed fines increased the Marshall and Hveem stability values at the optimum asphalt content. An increase in angularity in the fine aggregate also increased the minimum void percentages and increased the optimum asphalt contents.

Field[15] conducted a study to determine the effect of variation of crushed aggregate percentages in asphalt concrete mixtures. He found that replacing uncrushed aggregates with crushed aggregates increased the stability and increased the void content and voids in mineral aggregate for a given asphalt content. The higher VMA values allow more asphalt in the mix which improves the durability of the asphalt concrete pavement.

Gaudette and Welke[16] conducted a laboratory study that determined the effect of crushed faces on the stability of asphalt concrete mixtures. The authors evaluated the relationship between the number of crushed faces on coarse aggregate to stability and the percentage of crushed aggregate to stability. They concluded that the stability of the mixture increased significantly when the percentage crushed aggregates was increased from 0 to 50 percent. The number of crushed or fractured faces, whether it was 2, 3 or more, had no added effect on the stability when less than 50 percent crushed aggregate was used. Above 50 percent crushed aggregate, the aggregates with three or more fractured faces produced mixtures with increasing stability while the stability for mixtures with two or less fractured faces tended to level off.

Maupin[17] conducted a laboratory study to evaluate the effect of particle shape and surface texture on the fatigue behavior of asphalt concrete. The study used three different particle shapes, round, subangular, and angular. Asphalt concrete mixtures were produced with uncrushed gravel (round), limestone (subangular), and slabby slate (angular). Beam specimens were prepared and tested with constant strain fatigue. The laboratory study concluded that rounded gravel mixture had a longer fatigue life than the other mixtures.

Shklarsky and Livneh[18] conducted a laboratory study involving sands and gravels. They evaluated the difference between uncrushed and crushed coarse aggregate combined with natural sand and crushed fine aggregate. The authors found that replacing natural sand materials with crushed fine aggregate increased the stability and strength properties of Marshall specimens, reduced permanent deformation, improved resistance to wear, reduced asphalt content sensitivity, and increased voids. They also concluded that replacing uncrushed coarse aggregate with crushed coarse aggregate did not significantly improve the asphalt concrete mixture.

Kalcheff and Tunnicliff[19] conducted a laboratory study to determine the effects of crushed aggregate size and shape on properties of asphalt concrete mixtures. They specifically evaluated the effect of coarse aggregate gradations, shape effects of fine aggregates, and effects of high mineral filler content. The laboratory specimens were produced with Marshall and Hveem methods using aggregate blends composed of natural and manufactured sands. The optimum asphalt content was approximately the same for natural sand mixtures and manufactured sand mixtures if the sands had similar particle shape. The optimum asphalt content was higher if the manufactured sand had more angular particles. The authors found that asphalt concrete mixtures containing crushed fine aggregate were more resistant to permanent deformation from repeated loadings than comparable mixtures containing natural sand (Figure 1). The behavior of the asphalt concrete mixture was improved when manufactured sands replaced natural sands.

Lottman and Goetz[20] evaluated the effect of crushed gravel fine aggregate on the strength of asphalt mixtures. The authors found that the strength of asphalt mixtures was increased when mixtures contained crushed gravel fine aggregate instead of natural sand fine aggregates. They stated that the increase in strength was attributed to the angularity and the roughness of the crushed fine aggregate. The authors recommended that some amount of crushed fine aggregate be used with natural sands in asphalt mixtures to produce sufficient stability for high quality pavements.

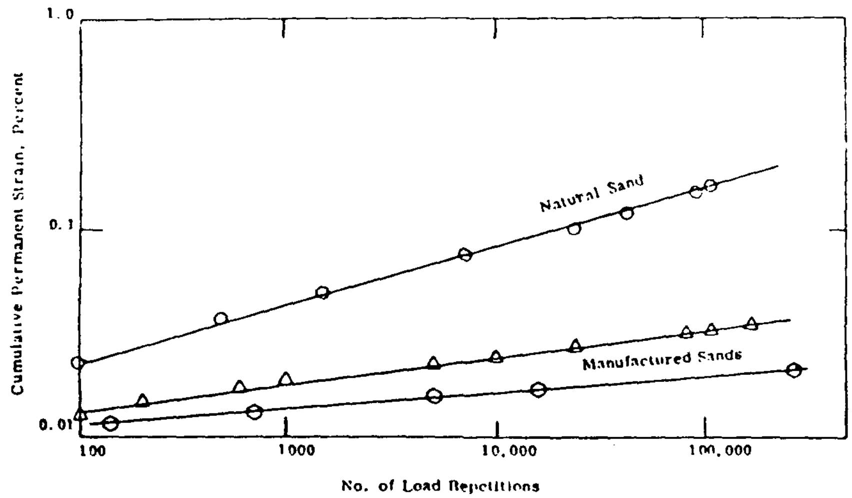


Figure 1. Typical relationship between permanent deformation and type of sand[19]

Button and Perdomo[21] conducted a study to evaluate the effects of natural sands on permanent deformation and to quantify the influence on resistance to plastic deformation when natural sand is replaced with crushed fine aggregate. The study showed that total deformation and rate of deformation increased as the percentage of natural sand increased (Figure 2). The texture, shape, and porosity of the fine aggregate were major factors controlling plastic deformation in asphalt concrete mixtures. The authors recommended replacing natural sand material with manufactured sand to increase the resistance of the asphalt concrete pavement to permanent deformation.

Kandhal and Wegner[22] conducted a study to determine the effect of crushed aggregate on properties of asphalt concrete for the Pennsylvania Department of Transportation. They found that replacing natural sand with crushed sand improved the Marshall stability and reduced permanent deformation. The authors also concluded that replacing uncrushed coarse aggregate with crushed coarse material did not significantly improve the asphalt mix properties.

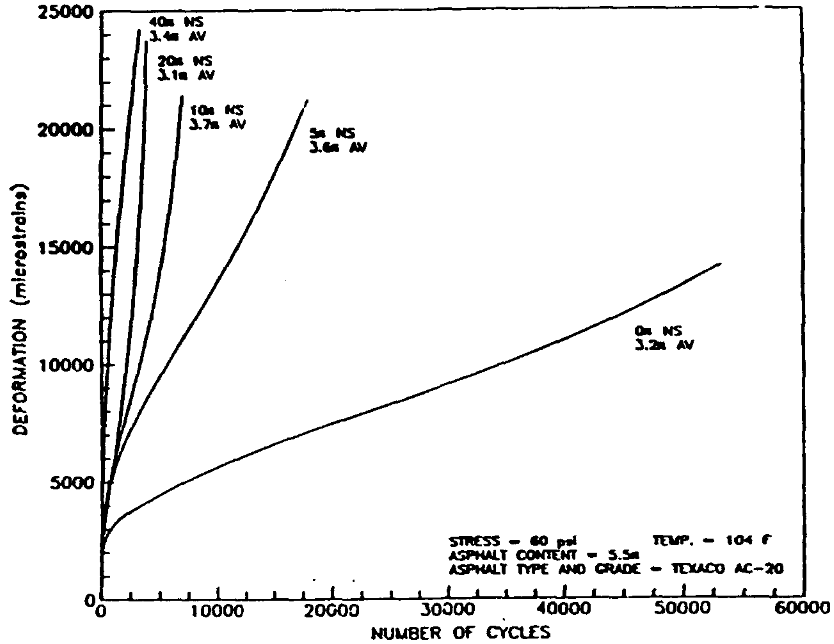


Figure 2. Relationship between pavement deformation and natural sand content[21]

Ahlrich[23] conducted a laboratory study to determine the influence of various amounts of natural sands on the engineering properties of asphalt concrete mixtures and to set quantitative limits of natural sand to prevent unstable mixtures and reduce rutting potential. The study indicated that the use of natural sand materials decreased the stability and strength characteristics of asphalt concrete mixtures and that replacing natural sand materials with crushed sand materials increased the resistance to permanent deformation. The author concluded that to maximize the reduction in rutting potential for heavy duty pavements (airports), all aggregates should be crushed. He also stated that if natural sands were to be used, a maximum limit of 15 percent by weight should be specified.

AGGREGATE QUALITY

Amirkhanian, Kaczmarek, and Burati[24] conducted a laboratory study to investigate the effects of LA abrasion values on the strength of asphalt concrete mixtures. Laboratory specimens were prepared according to the Marshall procedure to evaluate high and low LA abrasion values and degradation of extracted aggregates. The Marshall specimen were tested using the resilient modulus and indirect tensile tests on dry and conditioned specimen. The authors concluded that there was not a significant difference in resilient modulus and indirect tensile test results when comparing high LA abrasion values to low LA abrasion values. They also concluded that degradation of aggregates with high LA abrasion values was not significant when compared to low LA abrasion values.

Rollings[3] and Dolar-Mantuani[25] reported that the sulfate soundness test is used in many specifications but that it does not always accurately predict performance. They reported that the sulfate soundness test cannot clearly discriminate between aggregates that are susceptible to freezing and thawing and those that are not.

Rollings[3] stated that cohesive fines in aggregates were detrimental to the pavement's performance. Silt and clay sized particles are generally not allowed or limited in conventional asphalt aggregates to eliminate some construction, durability, and stability problems. These fine aggregates usually require extra asphalt for binder and extra effort to process before using in asphalt mixtures.

Brown and Graham[26] conducted a laboratory study to evaluate the relative benefits of using loess filler in sand asphalt mixtures. This study was conducted because results from the U.S. Army Corps of Engineers New Orleans District had shown that asphalt mixtures with loess material were more impervious to water than other mixtures. This study concluded that loess filler did improve the stability, tensile strength, and water susceptibility of sand mixtures. Although the loess material did improve the sand mixtures, conventional limestone dust filler produced better asphalt mixtures. The authors concluded that loess filler could be used to improve sand asphalt mixtures if limestone dust was not available.

MATERIAL AND MIXTURE TESTS

Boutilier[27] conducted a laboratory study to determine the relationship between the Particle Index developed by Huang[28] and the properties of asphalt concrete mixtures. The Particle Index is a function of the aggregate shape, texture, and angularity. This value is larger for aggregates that are more irregular, angular and rougher. The study indicated that there was a definite relationship between the Particle Index values and the properties of asphalt concrete mixtures. Figure 3 illustrates the relationship between Particle Index and Marshall stability and flow.

McLeod and Davidson[29] also conducted an extensive laboratory study to determine the relationship between Particle Index and asphalt concrete mixtures. The authors concluded that aggregates with rounded particles and smooth surface textures have a particle index of 6 or 7 or less, while aggregates with highly crushed angular particles have a particle index of 15 to 20 or more. They illustrated a distinct relationship between particle index and Marshall stability in Figure 4. They also concluded that the particle index of fine aggregate has a greater influence than the particle index of coarse aggregate on Marshall stability.

Meir and Elnicky[30] conducted a laboratory study to evaluate various test methods that provide information about the shape and surface texture of fine aggregates for asphalt mixtures and relate these properties to asphalt concrete properties. The authors concluded that the shape and surface texture of fine aggregate can be evaluated by a number of tests. These tests include the National Crush Stone Association procedure, Particle Index method, Rex and Peck Tim Index, and the void ratio method of Western Technologies. The direct shear test did not produce acceptable results.

Kandhal, Motter, and Khatri[31] conducted a laboratory study to quantify the particle shape and texture of various natural and manufactured sands using the Particle Index test, and the National Aggregate Association's (NAA) Methods A and B. They concluded that a Particle Index value of 14 seems to be the division between natural and manufactured sands. The NAA Methods A and B also divide the natural and manufactured sands with void contents of 44.5 and 48.3 respectively.

Winford[32] conducted a laboratory study to quantify particle characteristics and to evaluate relationships between these characteristics and permanent deformation and to recommend a test method for particle characterization. He concluded that the angle of internal friction derived from the direct shear test provides a reliable partition between natural and manufactured sands. He also concluded that a composite Particle Index value of 14 was the separation between natural and manufactured sands. NAA Methods A and B also correlated very well with the Particle Index test. He determined that the direct shear test was the simplest, quickest, and cheapest method for determining fine aggregate angularity and surface texture. The author also developed several relationships between the percentage of crushed aggregates and permanent strain or deformation. A relationship for uncrushed coarse aggregate and crushed fine aggregate is shown in Figure 5.

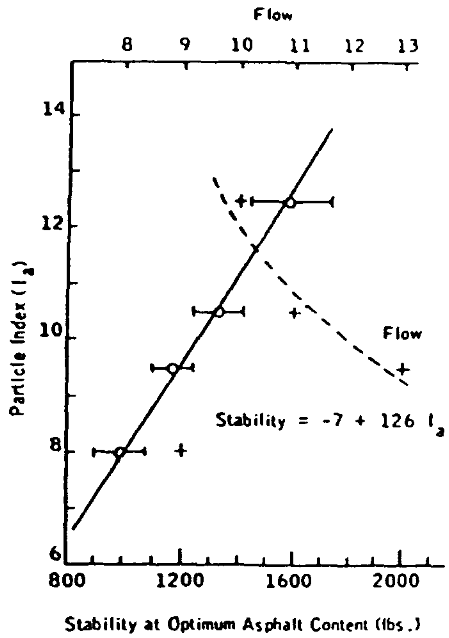


Figure 3. Relationship between Particle Index and Marshall stability and flow[27]

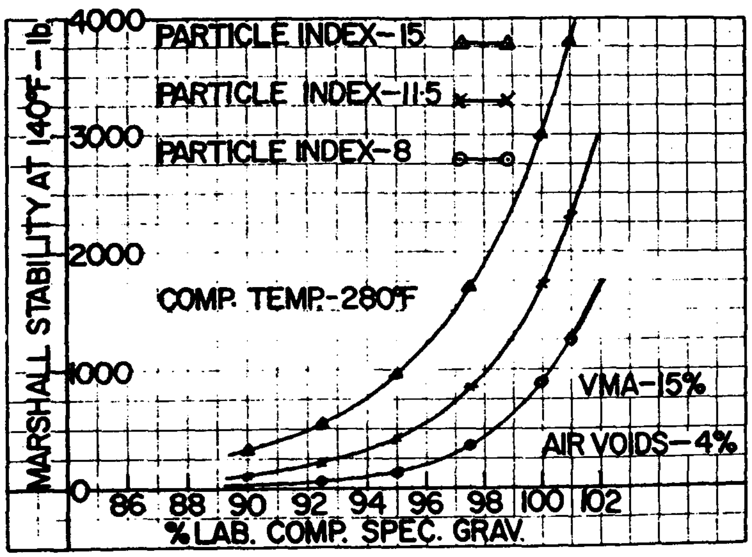


Figure 4. Relationship between Marshall stability and increasing Particle Index values[29]

Marks, Monroe, and Adam[33] conducted a laboratory evaluation that analyzed the effects of crushed particles in asphalt concrete mixtures. The laboratory tests included Marshall stability, indirect tensile, resilient modulus, and creep tests. Results of the study indicated the stability values increased substantially as the percentage of crushed aggregate increased. The resilient modulus data did not correlate with the percent of crushed particles or indicate resistance to rutting. Data from the creep test indicated rutting potential was very dependent on the percent of crushed aggregate (Figure 6).

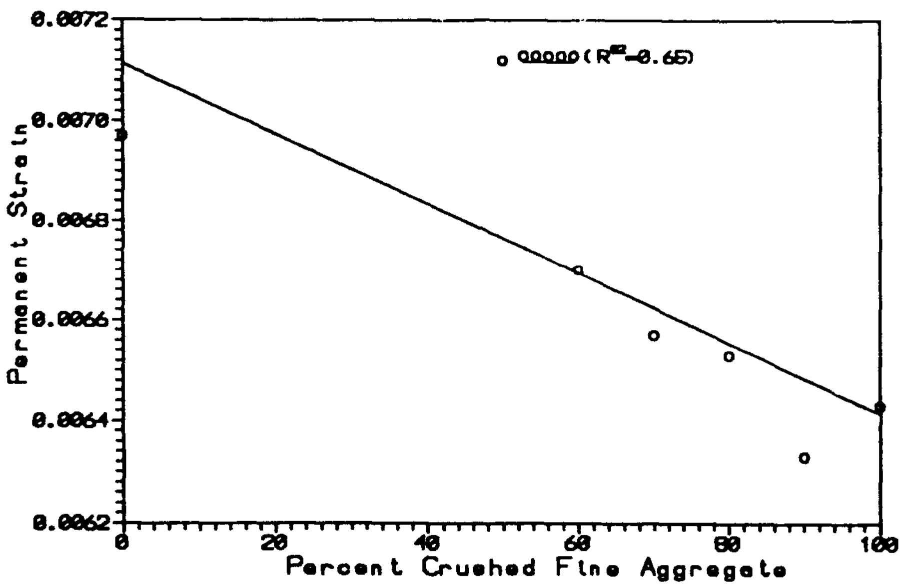


Figure 5. Pavement deformation of uncrushed coarse aggregate mixtures versus percent crushed fine aggregate[32]

Ahlrich[23] found that the amount of natural sand did affect the results of the indirect tensile, resilient modulus and unconfined creep-rebound tests. The indirect tensile results indicated a reduction in mixture strength as the percentage of natural sand increased. The resilient modulus test results were very inconsistent and provided no discernable trend. The unconfined creep-rebound test results indicated a strong relationship between the percentage of natural sand and rutting potential. The axial and permanent deformation values increased significantly as the natural sand content increased. The creep modulus value decreased significantly as the percentage of natural sand increased.

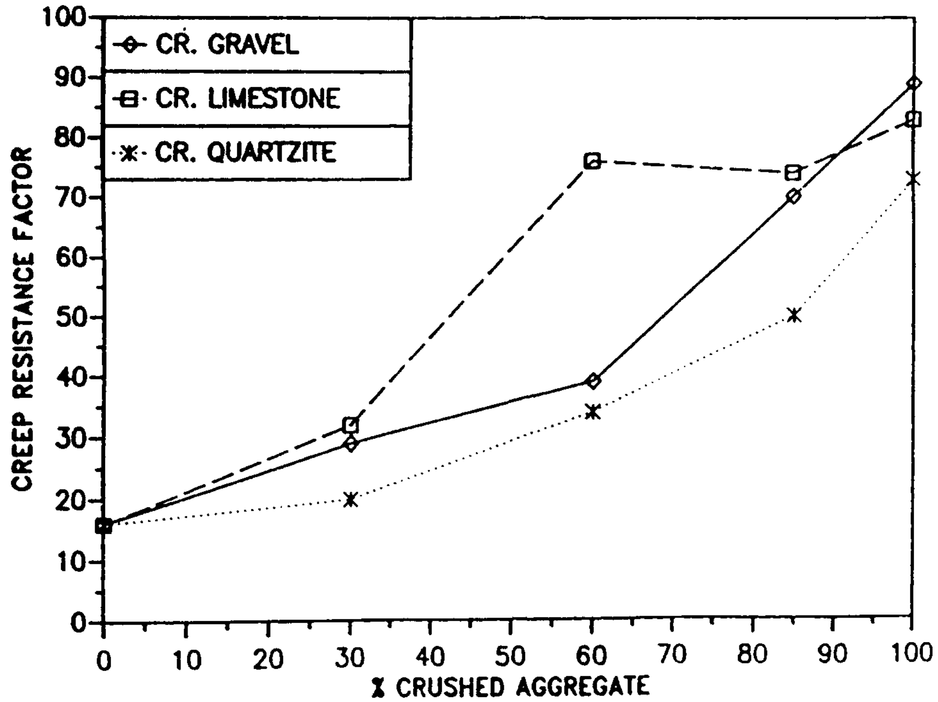


Figure 6. Relationship between creep resistance factor and percent crushed aggregate[33]

FIELD PERFORMANCE

Foster[34] evaluated the effect of fine aggregate on the strength of dense-graded asphalt concrete mixtures in field test sections at the U.S. Army Engineer Waterways Experiment Station (WES). The study involved constructing and trafficking field test sections constructed with three asphalt mixtures, a sand asphalt mix and two coarse aggregate mixtures containing the same fine aggregate. Based on the pavement's performance after trafficking, the author concluded that the true capacity to resist traffic induced stresses is controlled by the characteristics of the fine aggregate. These results agreed with findings from earlier tests at WES that were conducted during the development of the Marshall procedure[35].

Grau[4] evaluated the effects of natural sands and fine aggregates in field test sections. This study demonstrated that increases in amounts of natural sand and finer sand gradations produced less stable mixtures. A significant decrease in stability occurred when uncrushed gravel and natural sand were used together. The stability values of asphalt concrete mixtures increased significantly when crushed sand was used in place of natural sand.

Cross and Brown[36] conducted a study to evaluate aggregate properties that affect pavement rutting. Samples from 42 pavements that had been in service for more than 5 years were tested to determine aggregate and mixture properties. The authors concluded that aggregate properties do not significantly affect the rutting potential when in-place air voids are below 2.5 percent. They did state that the percent of fractured faces of the coarse aggregate did affect the rate of rutting, as the percent of crushed faces decreases the rate of rutting increases (Figure 7). The authors also concluded that as the angularity of fine aggregate decreases the rate of rutting increases (Figure 8). They concluded that higher percentages of crushed coarse aggregate and crushed fine aggregate reduced the potential for rutting.

Ahlrich[37] evaluated a new asphalt overlay that had been constructed for a military airfield parking apron to determine the effects of aggregate properties on rutting. Immediately after being opened for traffic, the new asphalt overlay exhibited significant deformation and depressions. A recompaction analysis was conducted on the in-place asphalt concrete material. The author concluded that the poor performance of the asphalt concrete was due to an improperly designed and produced asphalt mixture. The job-mix-formula (JMF) for the surface and intermediate course materials required 52.5 and 35 percent natural sand by weight, respectively. An analysis of the extracted aggregates determined that the amount of natural sand in the in-place material was between 30 and 40 percent. The excessive amount of natural sand was determined to have been the primary cause of premature rutting.

Ahlrich[38] investigated pavement distresses at a military airfield in Florida. The runways had been rehabilitated and resurfaced with asphalt concrete. Within 1 year, significant amounts of loose fine aggregate appeared on the surface. The performance of the overlay was unacceptable due to the raveling of the asphalt surface. A laboratory analysis of the in-place material was conducted to determine the possible causes of the pavement distresses. The author concluded that the poor performance was due to several factors: 1) low field density and high in-place voids, 2) coarse aggregate gradation, 3) excessive amount of natural sand (20 to 30 percent), and 4) low asphalt content.

Brown[39] conducted an investigation that evaluated a pavement failure that had occurred on three heliport runways in Alabama. These heliport runways had been resurfaced with 1.5 in. of asphalt concrete. Shortly after the pavement resurfacing, the helicopter landings began to damage the surface. This damage varied from scuffing the surface to gouging 1 in. deep. A laboratory analysis was conducted on pavement samples to evaluate the quality of the mixture. The analysis of the aggregate indicated that a fine aggregate gradation had been used and that an excessive amount of natural sand (45 to 50 percent) had been used in the mixture. The author concluded that the excessive amount of natural sand was the most important factor that led to the early pavement failure.

Brown[40] evaluated an existing pavement to determine the possible causes of pavement cracking in an airfield taxiway in California. The pavement surface had slippage cracks that penetrated only through the top layer and a large amount of hairline cracks that occurred during compaction. An investigation of the JMF indicated that 37 percent natural sand by weight had been used in the mix. A laboratory analysis was conducted on materials from areas that had cracked and areas that had not cracked. The primary difference between the mixtures was the amount of natural sand. The satisfactory pavement had a natural sand content of 23 percent while the cracked pavement had a natural sand content of 33 percent. The author concluded that the slippage cracks were due to an improper bond and that the hairline cracks were caused by a tender mix which had too much natural sand.

Anderton[41] conducted an investigation to determine the causes of pavement rutting in a roadway in Colorado. In less than 2 years moderate rutting (1/2 to 3/4 in.) had occurred in the wheelpaths. Pavement samples from areas with 3/4 in. rutting and no rutting were evaluated to determine the causes of this pavement deformation. An evaluation of the aggregate in the asphalt mixtures indicated that the mixture with moderate rutting had a natural sand content of approximately 35 percent while the pavement sample with no rutting had a natural sand content of 24 percent. The author concluded that the excessive natural sand contents were a primary factor that contributed to the pavement deformation.

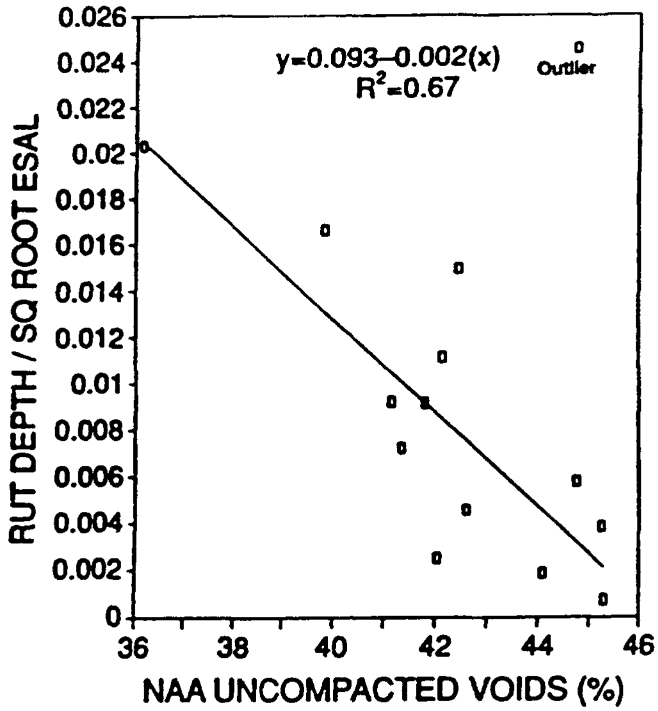


Figure 7. Relationship between NAA uncompacted voids and rate of rutting[36]

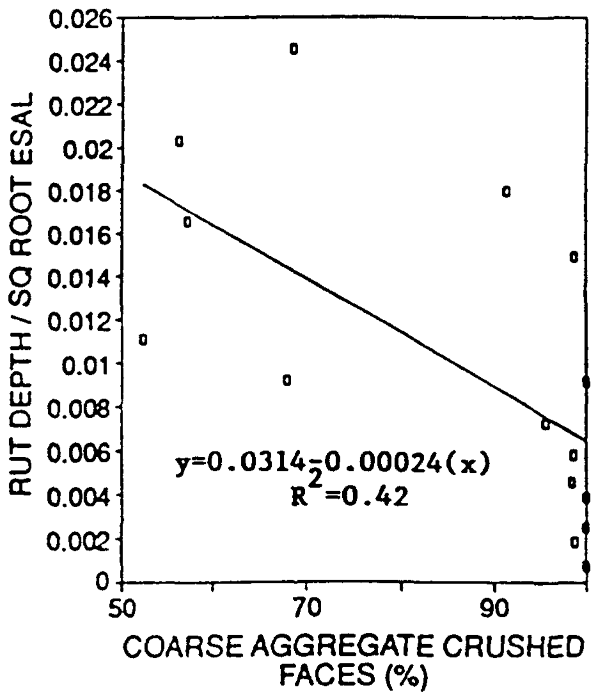


Figure 8. Relationship between coarse aggregate crushed faces and rate of rutting[36]

EFFECTS OF AGGREGATE PROPERTIES ON BASE COURSE MATERIALS

The base course is a major structural element of a flexible pavement. It must be stable under the high wheel loads of aircraft, and it must distribute the applied surface loads to the underlying layers. The asphaltic concrete surface is primarily a relatively thin wearing surface while the base course is primarily a major structural member. A failure in the base course is a major problem since it directly affects the load carrying capacity of the pavement and it is difficult to repair. Consequently, considerable conservatism is usually warranted for materials to be used in airport base courses. At the same time, a large quantity of aggregates are used in the base course of modern airport pavements, so the cost of these materials used in the base course are generally kept as low as possible.

FAA requirements for a "Crushed Aggregate Base Course" are shown in Table 1 where they are compared to the Corps of Engineers requirements, an ASTM standard specification, and a sample highway department specification. Generally, the specifications for the materials to be used on airports or airfields (FAA and Corps of Engineers) tend to be tighter than those for highway uses. This is reflected in the coarser gradations with control on material passing the No. 200 sieve, tighter Atterberg Limit values, and restrictive limits on aggregate quality. These requirements for higher quality in the base course for airports and airfields compared to highway requirements reflects the higher loads to which airfields are exposed. Much of the development of these requirements, however, was largely empirical and experience-based and dates back to the 1940's and 1950's. Since then there has been an appreciable effort trying to model granular base course behavior for analytical efforts[42], but less effort has gone into examining the effects of specification and quality of base course material on airport performance and cost. With the increasing scarcity and cost of high-quality aggregate, it has become increasingly more important to consider the actual needs and benefit of each specification requirement for aggregates to insure cost-effective pavement construction.

GRADATION

Pavement base courses have generally been desired to be dense graded so that they achieve the maximum density and strength. The maximum density of a graded soil or aggregate has generally been determined by the following relationship and which has been referred to as the "power grading law," "Talbot Equation," or "Fuller Curve"[7,43,44,45].

$$p = 100 \times \left(\frac{d}{D_{max}}\right)^n$$

where

p = percent of material smaller than d (i.e., percent passing d)

d = grain size in question (use consistent units for all sizes in equation)

D_{max} = maximum size aggregate used in material

n = a power

The maximum density for the aggregate generally exists when n is equal to 0.45 to 0.50.

Figure 9 shows the current FAA P-209 base course gradation for nominal 2-in. maximum size aggregate with the above equation plotted for n equal to 0.30 to 0.60. Clearly the shape and location of the allowable gradation bands are influenced by the predictions for the theoretical maximum density, but specification of grading limits purely to meet n values of 0.45 to 0.50 would be extremely restrictive and expensive.

Consequently, to achieve practical specifications, behavior of base course aggregate gradations in the field had to be evaluated to supplement the theoretical considerations. Highway experience formed the basis for most base course specifications, but such experience was not totally satisfactory for the heavier loads and tire pressures of aircraft. Consequently, Corps of Engineers full-scale trafficking tests[46,47,48,49] and airport field experience combined with highway recommendations led to the adoption of current airport base course gradations.

The percentage of material passing the No. 200 sieve (fines) is also an important crucial parameter governing the behavior of base course gradations. This was recognized early and the optimum percentage of fines to achieve density is higher than the optimum for strength[50]. Triaxial testing of base course material found that depending on the specific gradation and state of stress, a critical fine content exists between about 5 and 15 percent[51]. Above this critical value, deformations under load increase very rapidly. Ferguson also reported that the value of the critical fine content decreased as the ratio of vertical to confining stress increased. This implies that a more heavily loaded airfield base course should have a lower fine content than would a more lightly loaded highway base course. Laboratory tests by

TABLE 1. SELECTED BASE COURSE REQUIREMENTS FROM DIFFERENT ORGANIZATIONS

Requirement		FAA[1]	COE[2]	ASTM D 2940[3]	N.C. Type A[4]
Gradation (% Passing)					
2 in.		100	100	100	--
1-1/2 in.		95-100	70-100	95-100	100
1 in.		70-95	45-80	--	75-97
3/4 in.		55-85	--	70-92	--
1/2 in.		--	30-60	--	55-79
3/8 in.		--	--	50-70	--
No. 4		30-60	20-50	35-55	35-55
No.10		--	15-40	--	25-45
No.30		12-30	--	12-25	--
No. 40		--	5-25	--	14-30
No. 200		0-8	0-10	0-8	4-12
Atterberg Limits (%)					
Liquid Limit		≤25	≤25	≤25	≤35
Plastic Limit		≤4	≤5	≤4	≤6
Aggregate Quality					
Crushed Particles (%)		≥90	≥50	≥75	--
LA Abrasion (%)		≤45	≤50	--	≤55
Flat and Elongated	Particles (%)	≤15	≤30	--	--
Sulfate Soundness	5 cycles (%)	≤12	--	--	≤15

Notes:

1. Federal Aviation Specification Item P-209, "Crushed Aggregate Base Course," AC 150/5370-10A.

2. Corps of Engineers Guide Specification, Military Construction CEGS-02241, "Stabilized-Aggregate Base Course," Stabilized refers to compaction not chemical stabilization.

3. "Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airfields."

4. North Carolina Standard Specification for Roads and Structures, Section 1010, "Aggregate for Non-Bituminous Flexible Type Bases."

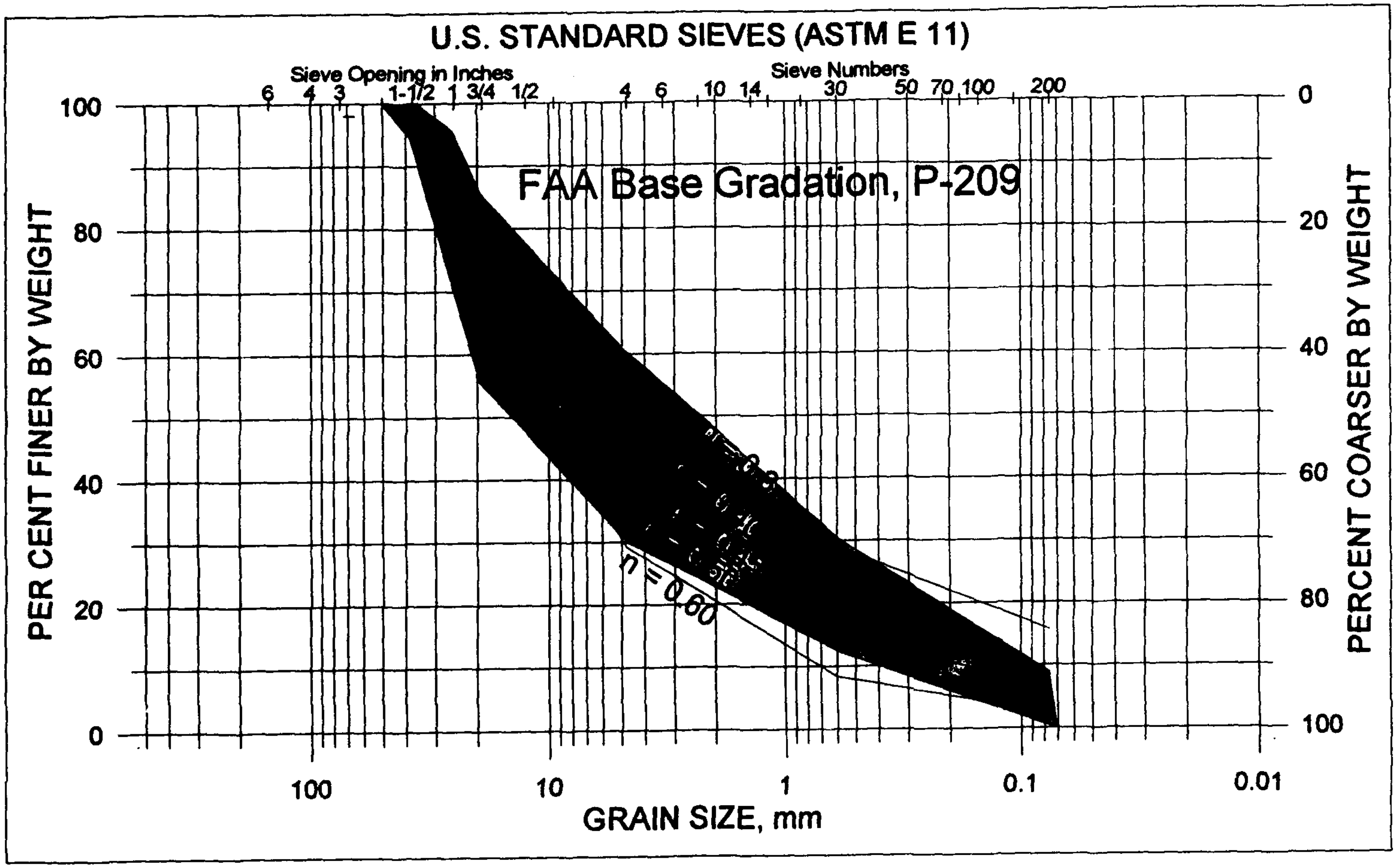


Figure 9. FAA P-209 base course gradation with various maximum density lines

Barksdale indicated that at a constant fines content, coarser gradations tended to rut less than finer ones[52].

Pavement drainage is one task commonly accomplished by base courses, and criteria for drainage are commonly based on work by Casagrande and Shannon[53]. Drainage is once again becoming a major topic of design and research interest for highway and airfield pavements, and the fine content of the base course has a major impact on the permeability of the base and its ability to accomplish drainage tasks[54,55,56]. Nettles and Calhoun[57] found that commonly specified Corps of Engineers base course materials with fines in the upper allowable range shown in Table 1 could not meet the drainage requirements originally suggested by Casagrande and Shannon and adopted by the Corps of Engineers. Consequently, it is clear both from the perspective of strength as well as permeability, the fines content has a major impact on the acceptability of a base course gradation.

The gradations used by the FAA for base courses are strongly rooted in empirical experience of what has worked well in the past but also include theoretical considerations of gradations that achieve maximum density and accelerated traffic studies to examine base course behavior under aircraft sized loads. The FAA gradation in Figure 10 allows somewhat finer gradations than the Corps of Engineers gradation, and the ASTM and North Carolina Highway gradation in Table 1 are contained within the fine side of the FAA gradation or allow somewhat finer gradations for base course material. A major difference between the gradations in Table 1 is the amount of allowable material allowed to pass the No. 200 sieve which, as discussed earlier, has critical impacts on strength and permeability. The FAA and ASTM gradations have the tightest limits (maximum 8 percent passing) while the North Carolina limits are the most liberal. The tight limits the FAA imposes on the material passing the No. 200 sieve are probably well justified to achieve strength under large aircraft loads and to help provide permeability. Overall the FAA requirements appear reasonable for the airport conditions. Probably allowing an increase in fines is not advisable due to their major impact on strength and permeability, but a different gradation could perform adequately. Because so much of the background for base course gradations is empirical and experience based, evaluation of nonstandard gradations is impossible without in-depth testing.

ATTERBERG LIMITS

The Atterberg limits of liquid limit and plastic limit and their difference, the plasticity index, are crude measures of soil consistency at

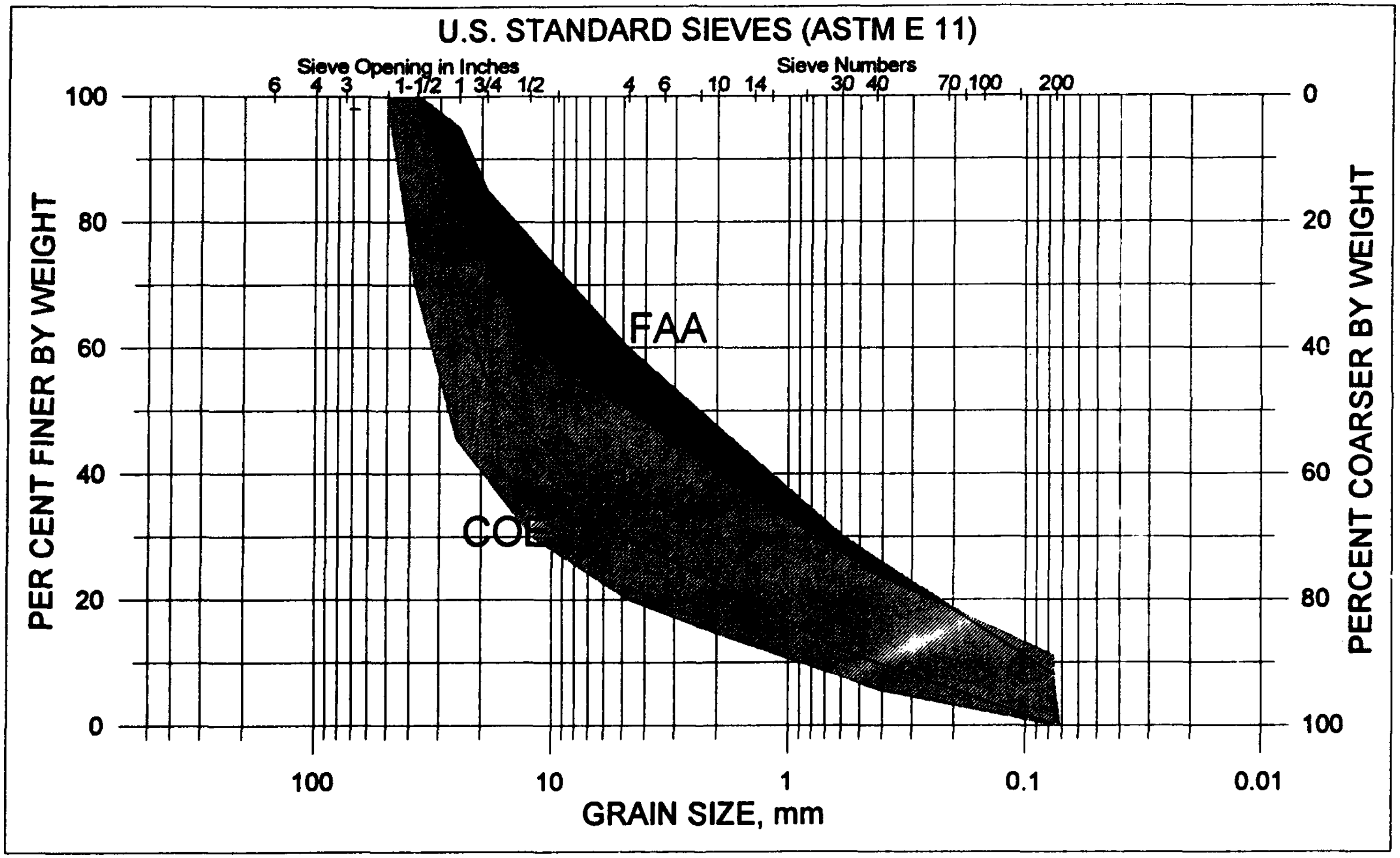


Figure 10. FAA and Corps of Engineers base course gradations

different moisture contents. These crude tests developed by the Swedish agronomist A. Atterberg are widely used in the soil mechanics and pavements fields to evaluate soils' behavior in the presence of water[58]. Figure 11 shows a typical relation illustrating the dramatic impact that the plasticity index has on strength of a gravel. Rollings and Rollings[59] give an example of two base courses used on airfields: one was a GC-GM with a plasticity index of 4 percent, and the other was a GC with a plasticity index of 12 percent. The first material maintained a 100 CBR value after soaking, and when inspected seven years after construction, the pavement with the GC-GM base course was performing well under heavy military traffic. The second material dropped to a 62 CBR when soaked even if compacted to 100 percent of modified AASHTO density. The airport that used this GC material suffered severe rutting and cracking after three years of traffic by light commercial and private aircraft.

The importance of limiting the Atterberg limits in materials in pavement materials has long been recognized and a plasticity index of 6 percent was often adopted as the dividing line between plastic and nonplastic behavior[60]. The Corps of Engineers reduced their limit to 5 percent to provide an additional measure of protection over the commonly used 6 percent (ASTM). Over the years, numerous outside consultants reviewing the Corps of Engineers flexible pavement program have endorsed this lower limit. The FAA draws its plasticity index tighter than the Corps of Engineers (4 versus 5 percent).

Like many of the decisions concerning the acceptable base course gradations, the acceptable values for Atterberg Limits represent consensus judgements and reflect various agencies' experience. The current FAA limits provides for a base course that is relatively insensitive to moisture, and any proposal to modify this must address the impact of strength loss due to moisture. Since so much of the development of these limits is empirical and experience based, testing is required to evaluate the impact of any variations from the existing requirements.

AGGREGATE QUALITY

Several requirements in Table 1 are specifically to insure a high quality aggregate that is essentially angular, cubical, and sound will be used in the base course of an airport. Of the examples in Table 1, the FAA has the most stringent requirement.

The requirement for a minimum crushed particle content insures that the material is angular and has a high degree of internal friction to resist load. However, the specific minimum requirements in Table 1 vary from 50 to 90 percent crushed particles. Figure 12 shows measured permanent deformations as a function of deviator stress from triaxial tests conducted by Georgia Institute of Technology and the Waterways Experiment Station[61,62]. These tests were conducted on crushed limestone, a gravelly sand, crushed porphyritemgranite, crushed biotite granite gneiss from two sources, and a fine silty sand blended with a crushed limestone. From this figure it is clear that a variety of factors can influence strength (type of aggregate, fines content, specific gradation) as well as crushing. However, as a general trend, crushing improves aggregate strength - for example, the gravel base course used in the AASHTO test underwent significantly more deformation under the same stress state than did the crushed stone base course[63] and the natural, uncrushed gravelly sand studied by Chisolm and Townsend showed more rutting potential than did the crushed limestone. Despite this generally observed trend there are many other factors that determine base course strength so that it is difficult to quantify the effect of crushing alone.

Flat and elongated particles tend to cause problems with compaction, particle breakage, loss in strength, and segregation. Specific definitions of elongated particles vary and suggested upper limits vary from 10 percent[52] to the FAA's 15 percent, to the Corps' 30 percent (Table 1).

Durability of the base course aggregate against degradation during construction, under traffic, and when exposed to weathering such as wetting and drying or freezing and thawing is provided through requirements such as the LA abrasion and sulfate soundness limits. Unfortunately, neither of these tests is sufficiently precise or representative of field conditions to predict the actual performance of the aggregate in the field[25,43,59,64]. Consequently, elimination of an aggregate from use solely on the basis of these tests may exclude perfectly good aggregates from use, and these tests are best used as screening tests. An aggregate that meets the FAA requirements for LA abrasion and sulfate soundness will probably be durable in the field, but additional testing and examination is warranted before an economical aggregate is excluded solely on the basis of these tests. Studies of aggregate durability have not identified any single test that correlates with field performance and have tended to conclude that a combination of tests is required and vary with rock type. The most promising approaches include some combination of index screening tests such as LA abrasion or sulfate soundness with petrographic examination and observation of field weathering characteristics[3,65,66]. Probably the most reliable indication of an aggregate's durability in a proposed project is its past history of in-service performance in similar structures exposed to conditions similar to those proposed. No single test or set of tests has yet been shown to predict field durability consistently.

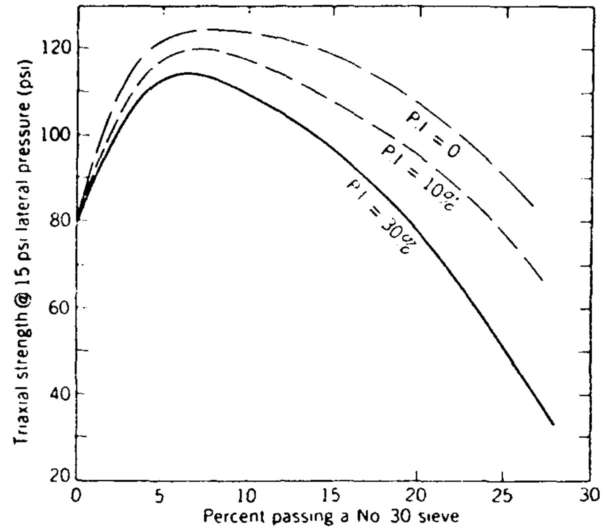


Figure 11. Relationship between plasticity index and triaxial strength[58]

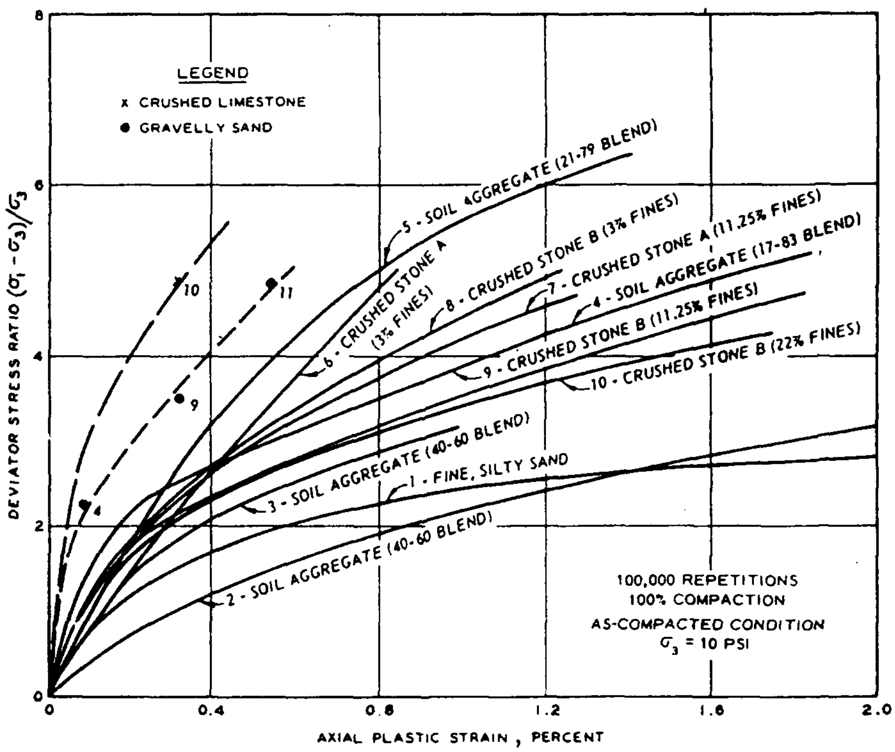


Figure 12. Relationship between permanent deformation and deviator stress[62]

POTENTIAL AREAS OF STUDY

Many base course specifications are highly empirical and experience based. When these specifications are met, there is a high probability of good performance; however, there are examples of other materials that do not meet the standard base course requirements performing well in the field[3,67,68]. With high quality aggregates becoming increasingly scarce and expensive it is important to examine all potential aggregate sources and exclude only those that will not provide satisfactory performance.

The FAA requirements for base courses reliably provides a high quality base material. In the preceding review of the origin of the FAA's requirements, it is clear that the limits on fines and on the Atterberg limits are well founded on engineering principles and experience that help insure strength to resist heavy aircraft loads and provide permeability of the base. Consequently, raising these limits does not appear to be a promising approach. The durability tests (LA abrasion and sulfate soundness) are effective screening tests but are not necessarily accurate predictors of field performance. However, considerable research effort to date has failed to develop a reliable method of testing and predicting aggregate performance. Therefore, a pragmatic approach that uses screening tests such as the ones in the FAA specification with more in-depth testing and examination of aggregates that fail the screening test coupled with an examination the aggregate's past performance appears to be the most promising present solution. The aggregate's gradation and the percentage of crushed particles appear to be the most promising area for study of using non-standard base course materials. Today, the performance of base course aggregates can be compared using tests such as the repeated load triaxial test[62], gyratory shear[69], or the confined repeated load deformation test (currently being developed at WES for this study) can be evaluated in the laboratory. These tend to be of comparative value only because no accepted criteria have been developed for linking laboratory tests of granular base course to field performance. Consequently, field trials are still needed. The use of substandard materials that fail to meet conventional criteria requires more testing and engineering effort than simply using the existing criteria, but with high-quality aggregates becoming increasingly scarce and expensive, such efforts are justified[2,3,68].

IMPROVEMENT OF SUBSTANDARD MATERIALS

Conventional stabilization techniques using lime, portland cement, bituminous materials, and fly ash have often been used to upgrade substandard materials to allow their use in the pavements. This is a widely used technique and ample criteria for this use is currently published by the FAA, other government agencies, and various trade associations. In Europe slag cements are commonly used for stabilization instead of portland cement because of slower setting and strength gain, reduced shrinkage, and lower cost[70]. Recently, an emulsion of portland cement, bitumen, and water has been marketed in France under the trade name Stabicol[71], but it is not yet available in the U.S. This composite product has the potential of providing relatively high strength and stiffness which has been lacking in bituminous stabilization without the shrinkage cracking problem that has plagued all hydraulic binders that have been used for stabilization.

Geotextiles offer a very strong potential method of reinforcing substandard base course materials. The basic literature covering these areas has been summarized by White[72] and Webster[73]. Discrete and continuous geofibers mixed with substandard base materials have the potential to strengthen the material and may be able to overcome poor gradation or lack of crushed particles in the materials. However, testing will be required to explore their potential for this application. Geowebs have demonstrated their potential to use low quality sand or other material and confine it to make a low grade base equivalent to a CBR of 50 to 80 material depending on the specific geoweb fill material[73]. A particularly promising test recently conducted for the FAA showed that geogrid reinforcing in the base significantly stiffened the material and improved performance. This is particularly encouraging for overcoming material with poor grading or inadequate crushing and appears to be a very viable way to reinforce a substandard material for use in a pavement base course.

The effect of non-standard grading and quantity of crushed particles needs to be better defined to evaluate how materials that fail to meet the standard requirements in these areas will perform under aircraft loading. Conventional stabilization techniques are available to upgrade some substandard materials to levels where they might be used in a pavement base course. Geotextile reinforcement and a new portland cement-bitumen emulsion have considerable potential to upgrade substandard materials for use in base courses.

EXPERIMENTAL PLAN

This study will attempt to define in engineering terms the impact of using marginal aggregates in asphalt concrete mixtures and base course materials for flexible pavements. Basically, the laboratory study will determine how much the asphalt concrete and base course mixture's strength has been reduced and to develop strategies to improve the performance of these mixtures with marginal aggregates to equal that of accepted standards. As directed by the FAA, the major emphasis will be on marginal aggregates for asphalt concrete mixtures rather than the base course materials.

ASPHALT CONCRETE MIXTURE

Item P-401 provides the FAA requirements for asphalt concrete mixtures. This specification requires a high quality, durable, clean, well-graded, crushed aggregate. This phase of the laboratory testing will consider the effects of departure from the requirements of the specification for the standard 3/4 inch maximum aggregate size gradation, the percentage of crushed aggregate particles, the amount of natural sand, and the amount of minus No. 200 material. The other standard aggregate requirements that are specified by Item P-401, LA Abrasion (ASTM C 131), sulfate soundness (ASTM C 88) and flat and elongated (ASTM D 4791) tests, will not be examined because these tests do not correlate particularly well with pavement deformation or rutting and field performance. Previous laboratory research and field investigation have indicated that poorly graded aggregate gradations, uncrushed particles, too much natural sand and excessive amounts of minus No. 200 material produce less than acceptable asphalt concrete mixtures and are susceptible to pavement deformation.

The aggregate sources for this phase of the laboratory evaluation will include limestone and gravel materials. The limestone aggregate will meet the requirements of Item P-401 and will serve as the accepted high quality aggregate. Uncrushed gravel and sand will be used as the marginal aggregate. All aggregate materials will be evaluated with the following tests:

a) LA Abrasion.
b) Sulfate Soundness.
c) Fractured Face Examination.
d) Flat and Elongated Particles.
e) Gradation.
f) Absorption.
g) Specific Gravity.

h) Particle Shape Index.

i) NAA Test for Particle Shape and Texture.

The aggregates from each source will be processed by screening to develop laboratory stock. The processed material will be used to fabricate the specific test gradations. The following are examples of the test gradations that were considered for evaluation:

a) Center of P-401 gradation band.

b) Coarse side of P-401 gradation band.

c) Fine side of P-401 gradation band.

d) Gradations coarser and finer of maximum limits.

e) Poorly-graded gradations.

f) Six gradations at the center of the P-401 gradation but with varying percentages of crushed and uncrushed aggregates.

g) Eight gradations at the center of the P-401 gradation but with varying percentages of natural sand.

h) Gradation at the center of the P-401 gradation but with an excessive amount of minus No. 200 material.

A Marshall mix design will be conducted on each test gradation and an optimum asphalt content will be selected based on a 75 blow compactive effort. The standard FAA mix design procedure will follow criteria in the Asphalt Institute Manual Series No. 2 (1989). The following laboratory tests will be conducted to evaluate engineering properties of each asphalt concrete mixture at the optimum asphalt:

a) Marshall Tests.

b) Resilient Modulus.

c) Indirect Tensile.

d) Confined Repeated Load Deformation.

e) Gyratory Properties.

f) Moisture Susceptibility.

This laboratory testing will determine the range of mix properties that would be expected using material meeting the P-401 specification and the impact of deviations on engineering properties by using marginal aggregates.

Candidate methods of upgrading selected marginal aggregates from above will be considered:

a) Asphalt Modification - stiffening the asphalt concrete by adding asphalt modifiers with SBS, polyethylene.

b) Hard Asphalt Cement - AC 40 asphalt cement.

c) Large Stone Asphalt Mixtures - Increase maximum aggregate size.

e) Stone Mastic Asphalt (SMA) - stone on stone contact.

BASE COURSE MATERIALS

Item P-209 provides the FAA requirements for crushed stone base course materials. This specification requires a high quality, 100 percent crushed stone or slag aggregate with a plasticity index (PI) of 4 percent or less. This phase of the testing will consider effects of departure from the gradation and crushed particle requirements of the specification. LA Abrasion (ASTM C 131) and sulfate soundness (ASTM C 88) correlate poorly with field performance so little progress could be expected by examining these area further. Previous research has shown that the PI and percent fines (minus No. 200 sieve) have a major impact on strength loss and permeability of granular bases when they become wet. Because of the serious implications of a base course failure, it is not recommended that the PI or percent fines be allowed to increase over current limits in Item P-209.

Two sources of aggregate will be used for this study. One will be crushed and will meet the requirements of Item P-209. The other will be uncrushed. Each aggregate source will be subjected to the following tests:

a) LA Abrasion.

b) Sulfate Soundness.

c) Specific Gravity.

d) Particle Shape Index.

e) NAA Test for Particle Shape and Texture.

f) Atterberg Limits on Minus No. 40 Material.

g) Fractured Face Examination.

The aggregates from each source will be processed by screening to develop laboratory stock on various sieve sizes. These processed aggregates will be blended to develop the specific test gradations. The following are examples of the test gradations that were considered for testing:

a) Center of P-209 gradation band, 100% crushed.

b) Coarse side of P-209 gradation band, 100% crushed.

c) Fine side of P-209 gradation band, 100% crushed.

d) Gradacions coarser and finer than maximum limits, 100% crushed.

e) One gap graded gradation, 100% crushed.

f) Four gradations at center of P-209 gradation but with varying percentages of crushed and uncrushed material.

Each gradation will be tested to determine compaction curves using ASTM D 1557, soaked and unsoaked CBR tests, and triaxial tests at approximately 100 percent modified density. This testing will determine the range of properties that would be expected using material meeting the Item P-209 specification and the impact of deviations on the engineering properties of the aggregate.

Candidate methods of upgrading selected marginal aggregate gradations from above will be considered:

a) Mechanical Reinforcement. This will include use of discrete fibers, continuous fibers, and grids.

b) Cement Stabilization. Conventional base course stabilization is covered in Item P-304 and requires 750 psi compressive strength at 7 days. Lower cement contents and strengths will be considered in this testing as a means to improve the marginal aggregates resilient modulus to within that of the Item P-209 aggregates.

DISCUSSION AND DESCRIPTION OF TESTING EQUIPMENT AND PROCEDURES

Several types of testing equipment and test procedures will be used to determine the effects of marginal aggregates on the engineering properties of asphalt concrete. Current state-of-the-art testing equipment will be used in addition to standard laboratory equipment and procedures generally used to conduct Marshall mix designs. This more complex testing equipment and sophisticated testing procedures will include the Corps of Engineers Gyratory Testing Machine (GTM), Automated Data Acquisition and Control Testing (ADACT) System, indirect tensile test, resilient modulus test, and confined repeated load deformation test. The laboratory equipment and test procedures that will be used in this study are described and discussed in the following paragraphs.

GYRATORY TESTING MACHINE

Compaction of asphalt concrete materials using gyratory method applies normal forces to both the top and bottom faces of the material confined in cylindrically-shaped molds. Normal forces at designated pressures are supplemented with a kneading action or gyratory motion to compact the asphalt concrete material into a denser configuration while totally confined. The U.S. Army Corps of Engineers has developed a method, procedure, and equipment using this compaction procedure[74,75,76].

The gyratory compaction method involves placing asphalt concrete material into a 4-inch-diameter mold and loading into the GTM at a prescribed normal stress level which represents anticipated traffic contact pressure. The asphalt material and mold are then rotated through a 1-degree gyration angle for a specified number of revolutions of the roller assembly. Figure 13 is a schematic of the gyratory compaction process. Military Standard 620 A Method 102 has correlated equivalent types of compaction and compactive efforts[77].

Gyratory Compaction	Marshall Impact Compaction
100 psi, 1-degree, 30 revolutions	50 blow per side
200 psi, 1-degree, 30 revolutions	75 blow per side

Model 4C and Model 8A/6B/4C Gyratory Testing Machines (GTM) will be used to compact all laboratory specimens in the marginal aggregate laboratory study. Previous research with the GTM has suggested that the laboratory tests will simulate field behavior and performance under traffic when asphalt mixtures are compacted at stress levels similar to anticipated field traffic conditions[35,77]. The gyratory compactive effort to be used in this laboratory evaluation will follow the standard guidance in ASTM D 1556 for the 75-blow compactive effort. The gyratory compactive effort will be set at the 200 psi normal stress level, 1-degree gyration angle, and 30 revolutions of the roller assembly. The asphalt concrete specimens produced with this compactive effort will satisfy the Marshall specimen dimensions of 4 inches in diameter and 2 1/2 inches thick. Figure 14 shows the WES Model 4C and 8A/6B/4C GTMS.

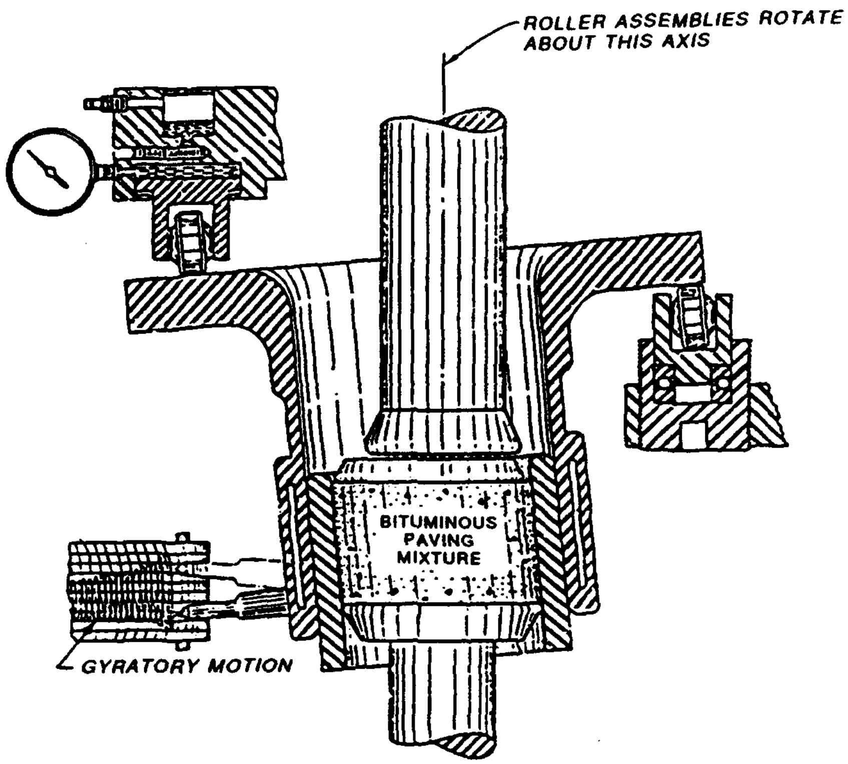


Figure 13. Schematic of Gyratory Compaction Process

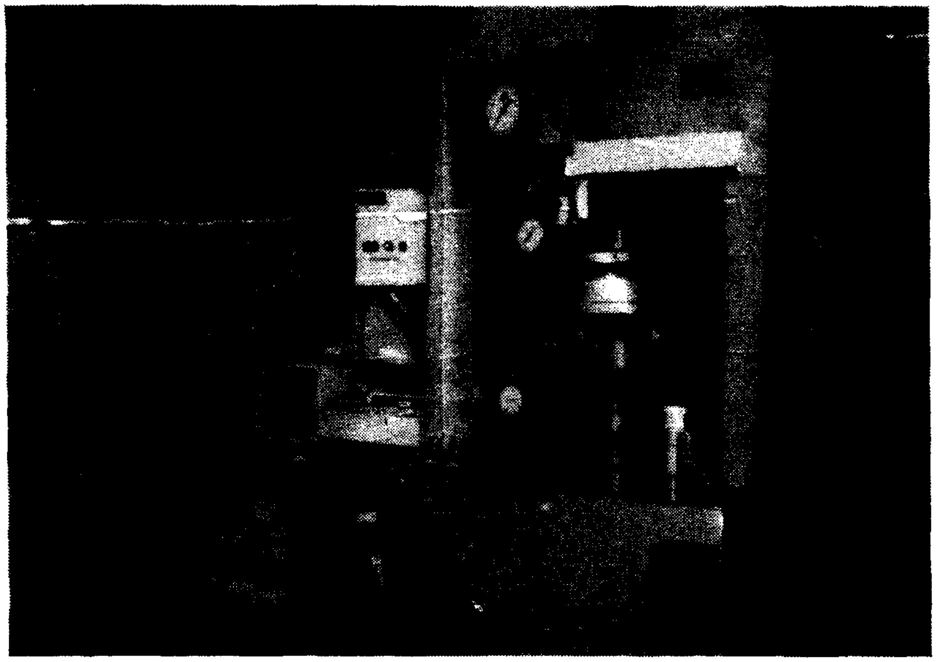
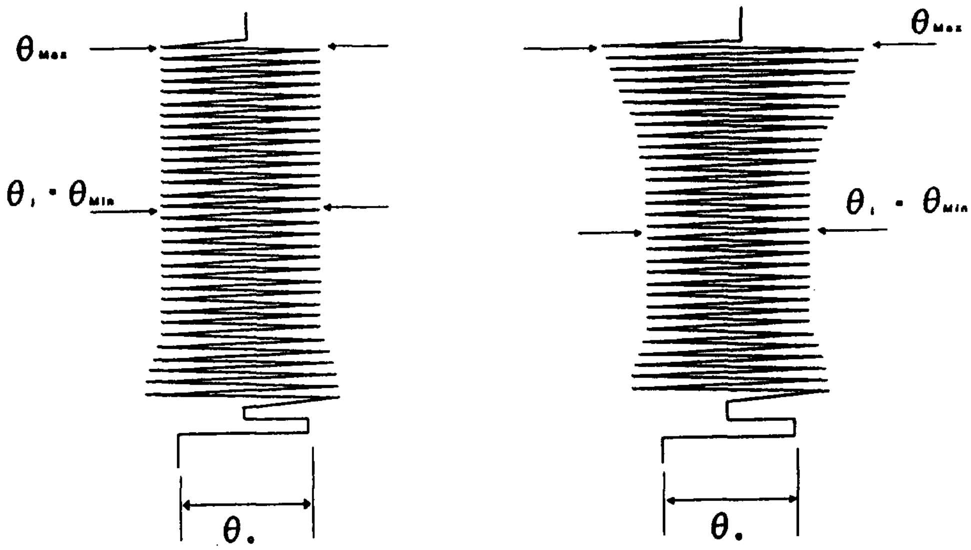


Figure 14. WES Model 4C and 8A/6B/4C Gyratory Testing Machines

The gyratory compaction method using the GTM produces a gyratory graph or gyrograph that can be used to evaluate the asphalt concrete mixture behavior during compaction. The gyrograph indicates the relative stability behavior of the mixture during the compactive effort. The gyrograph indicates an unstable mixture when the gyrograph spreads or widens. A gyrograph that does not spread is considered stable under that loading condition[74,75].

The gyrograph also produces two indices that describe the relative stability of an asphalt concrete mixture. The ratio of the final width to the intermediate width of the gyrograph is called the Gyratory Stability Index (GSI). A GSI value greater than 1.0 indicates an unstable mixture with a high asphalt content. The ratio of the intermediate width to the initial width is called the Gyratory Elasto-Plastic Index (GEPI). The GEPI value is an indicator of the quality of the aggregate. Figure 15 displays a typical gyrograph of a compacted asphalt concrete specimen.



θo • Initial shear strain (machine setting)
θi • Minimum shear strain (θMin)
θMax • Maximum shear strain

Figure 15. Typical Gyrograph[75]

AUTOMATED DATA ACQUISITION AND CONTROL TESTING SYSTEM

Previous research studies conducted in the Materials Research and Construction Technology Branch, Geotechnical Laboratory, had required accurately controlled laboratory testing and data acquisition[23,79]. A state-of-the-art computer-operated system was assembled to conduct modern, complex asphalt concrete mixture tests. This customed-designed computer-testing system is called the Automated Data Acquisition and Control Testing (ADACT) System. The ADACT System was specifically designed and organized to conduct three asphalt concrete mixture tests; indirect tensile, resilient modulus, and confined repeated load deformation. Figure 16 is an overall view of the ADACT System.

The MTS electrohydraulic closed-looped material system is the main component of the ADACT System. The loading sequences of the electrohydraulic system are controlled by an arbitrary waveform generator. The test loads are recorded by electronic load cells and the specimen deformations are measured by electronic linear variable differential transformers (LVDT). The ADACT System also includes electronic temperature control of the enclosed environmental chamber and real time color graphics.

The ADACT System is controlled by a 32-bit personal-computer (PC) designed to operate as the system's principal measurement and control station. Customized computer programs were developed to control the mechanics, monitoring systems, test data manipulations, and data storage for indirect tensile, resilient modulus and confined repeated load deformation tests. These programs were designed to reduce operator dependency and to allow the computer to be the single system control.

Figure 16. Overall View of Automated Data Acquisition and Control Testing System

INDIRECT TENSILE

Researchers in Brazil and Japan developed a testing procedure in 1953 to indirectly determine tensile strengths of materials[80]. The indirect tensile test involves placing a cylinder of material horizontally between two loading plates and loading the specimen across its diameter until failure. This loading configuration subjects the centerplane between the loading plates to a nearly uniform tensile field, and the resulting failure is a tensile failure in the material. This test procedure has been used to test soils, concrete, and asphalt concrete materials, and has been used by engineers to compute fundamental properties of materials. Figure 17 shows a schematic of the indirect tensile test.

ASTM Method D4123 provides guidance on indirect tensile testing of asphalt concrete mixtures[80]. This test procedure will be conducted on specimens produced at the optimum asphalt content for each aggregate blend. This test procedure is considered straight forward and generally produces consistent results. The indirect tensile test will be conducted on specimens at two test temperatures, 77°F and 104°F. These specimens will be cured in an oven at the appropriate temperature for 2 hours before testing.

The indirect tensile test requires that the specimens be positioned so that the loading plates are centered and the load is applied across the diameter of the specimen. The vertical load is applied at a constant deformation rate of 2 inches per minute until failure. The ultimate load will be recorded at failure and used to calculate the tensile strength. This testing procedure will be conducted on a minimum of three specimens for each of the twenty-two aggregate blends at both temperatures. Figure 18 shows the indirect tensile test.

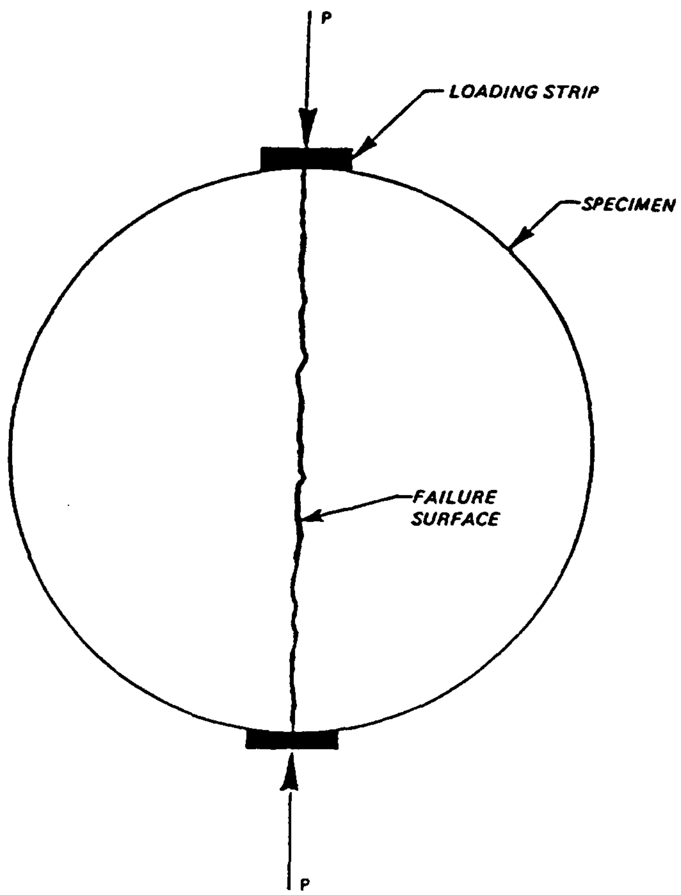


Figure 17. Schematic of Indirect Tensile Test

Figure 18. Indirect Tensile Test

The tensile strength is calculated according to ASTM D4123, as follows:

$$\text{Tensile strength} = 2P/\pi tD$$

where

P = ultimate load required to fail specimen (lb)
t = thickness of specimen (in)
D = diameter of specimen (in)

RESILIENT MODULUS

The resilient modulus test is used to evaluate the stiffness of asphalt concrete mixtures. The resilient modulus test procedure will be conducted according to ASTM Method D4123[30]. Higher resilient modulus values indicate that the asphalt mixture has a greater stiffness and a resistance to permanent elastic deformation. This test procedure also evaluates the effects of repeated loads on asphalt concrete mixtures. The resilient modulus test is considered a nondestructive test and allows the same specimen to be tested several times.

The resilient modulus test requires the specimens to be pre-conditioned at the desired testing temperature for 2 hours. The specimens are then positioned between the loading plates in the same manner as the indirect tensile test. Horizontal and vertical deformations are measured during the loading operation with LVDTs. Figure 19 shows the resilient modulus test.

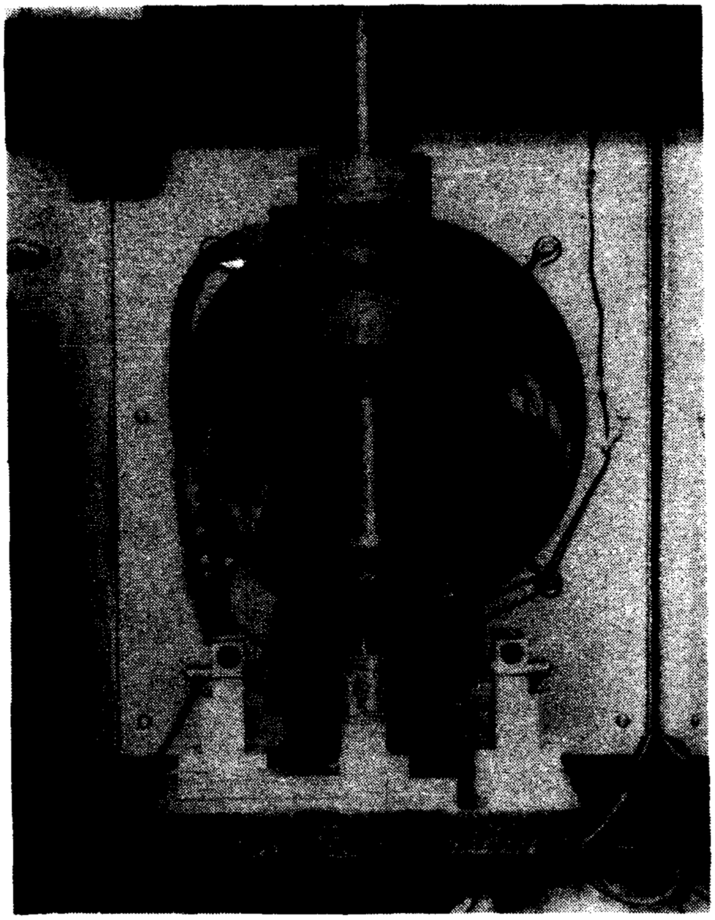


Figure 19. Resilient Modulus Test

The actual resilient modulus testing procedure for this study will involve the following: the specimens will be preconditioned by applying a repeated haversine waveform at a reduced load to obtain a uniform deformation readout; the magnitude of the load applied will be a percentage (15 percent for 77°F and 5 percent for 104°F) of the aggregate blend's tensile strength; the time of loading will be set at 0.1 seconds (representative time for actual pavement loadings); the loading frequency will be set at 1.0 Hz or 1 cycle per second;

and the haversine waveform will be applied by the arbitrary waveform generator as recommended by ASTM.

The resilient modulus test is conducted on a minimum of three specimens from each aggregate blend. Each specimen is tested in two positions, the initial position (0 degrees) and a rotated position 90 degrees from the initial position. Conducting the resilient modulus test in this manner allowed a total of six resilient modulus values to be determined. This procedure will be conducted at both testing temperatures, 77°F and 104°F.

The resilient modulus value is calculated using a modified version of the equation presented in ASTM D4123. The equation used in this study assumed a Poisson's ratio of 0.35 for 77°F and 0.45 for 104°F. The ASTM method suggests an equation that uses a Poisson's ratio that is calculated with horizontal and vertical deformations. The variability in the measured vertical deformation causes an inconsistency in the calculated resilient modulus value, thus producing unreliable data[82].

The resilient modulus value is calculated as follows:

$$E_{RT} = P\ (\upsilon + 0.27)\ /\ t\ \Delta\ H_T$$

where

E_{RT} = total resilient modulus of elasticity (psi)
P = applied repeated load (lb)
t = thickness of specimen (in)
ΔH_T = total recoverable horizontal deformation (in)
υ = Poisson's Ratio

CONFINED REPEATED LOAD DEFORMATION

The confined repeated load deformation test is used to evaluate the rutting potential of the marginal aggregate blends. This test equipment and evaluation was developed by WES specifically for this research on the basis of recent work at Auburn University that showed confined repeated load deformation provided the best laboratory indication of rutting[83].

The confined repeated load deformation tests will be performed on individual Marshall specimens that were 2.5 in. thick and 4 in. in diameter. These specimen were placed in the triaxial chamber with smooth, dense-graded paper on each end and a rubber membrane around the sides. The triaxial chamber will be then placed in an environmental chamber at 140°F for a minimum of 2.5 hours. The triaxial chamber is pressurized with a confining pressure of 40 psi for 30 minutes. Each specimen will be preconditioned with a 1.5 psi preload and then a 10 psi cyclic stress will be applied for 30 cycles. The cyclic or repeated load is applied with 0.1 second load application and a 0.9 second rest period. Figure 20 shows the confined repeated load deformation test.

The loading portion of the test applies a repeated cyclic load for 60 minutes and then the loading is released for 15 minutes for the rebound phase. The applied axial stress is 240 psi with a deviator stress of 200 psi. The deformations and loads will be recorded by the ADACT System at various times during the creep and rebound phases. These measurements are used to calculate stresses and strains and then converted into a creep modulus value. The confined repeated load deformation test will be conducted at 140°F. Figure 21 displays a typical strain versus time curve.

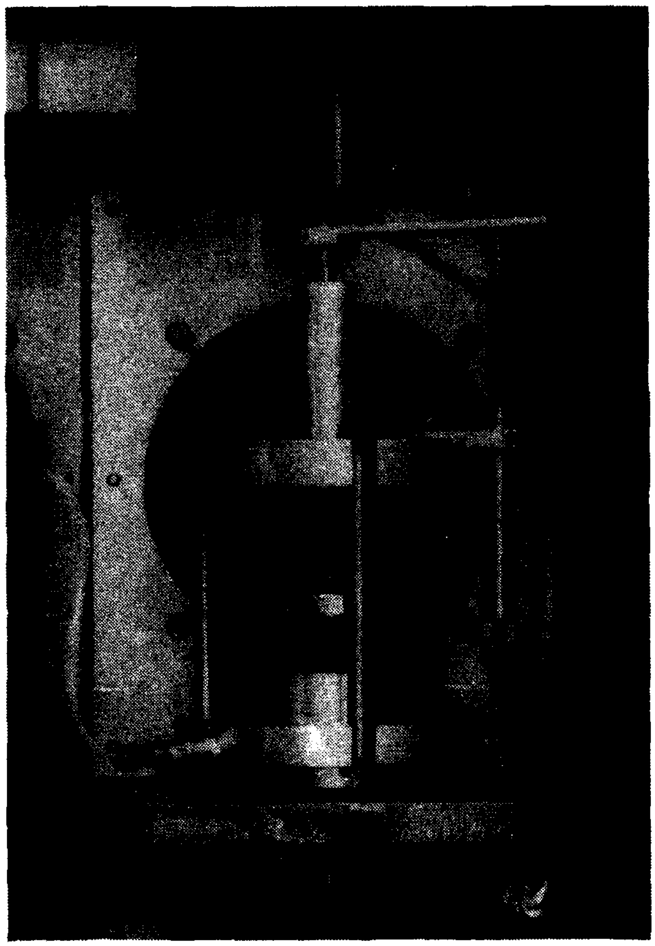


Figure 20. Confined Repeated Load Deformation Test

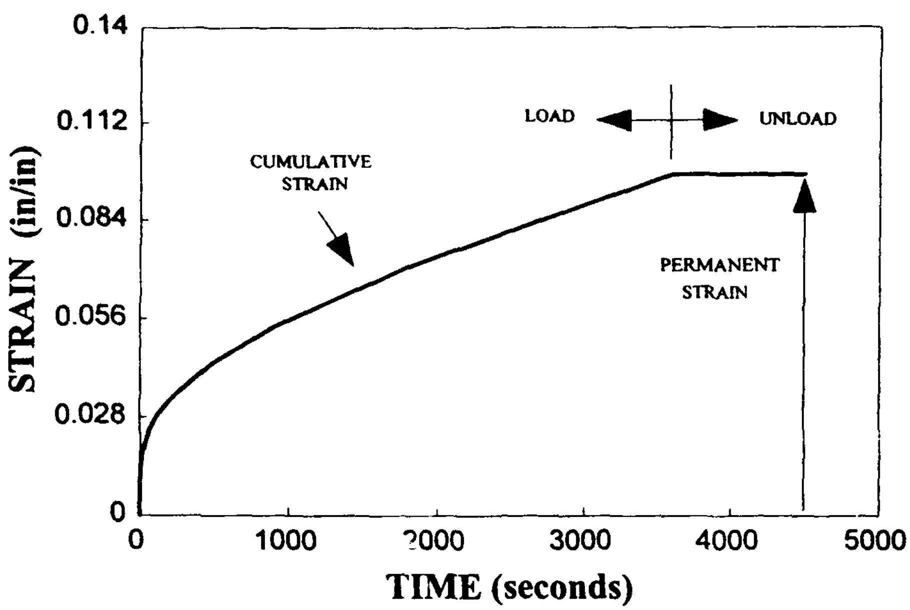


Figure 21. Typical Confined Repeated Load Deformation Curve

The results of the confined repeated load deformation test can be used in several ways to evaluate asphalt concrete mixtures. The amount of deformation during the creep phase indicates the asphalt mixture's potential for permanent deformation. Smaller axial deformations and lower creep deformation values indicate stable asphalt mixtures. The creep modulus value indicates the asphalt concrete mixture's stiffness. High creep modulus values should indicate minimum potential permanent deformation.

The creep modulus value is calculated as follows:

$$Ec = (S)(H)/D$$

where

Ec = creep modulus (psi)
S = vertical stress (load/contact area; psi)
H = height of specimen (in)
D = axial deformation (in)

PROJECT SUMMARY

This research study was divided into three phases: Phase I - Background Survey, Phase II - Laboratory Evaluation, and Phase III - Field Test Sections. Phase I has been completed and documented in this interim report. Phase II is currently being conducted and should be completed by March 1994. Phase II includes aggregate characterization tests, initial asphalt concrete mix designs, laboratory tests evaluating engineering properties and rutting potential, and evaluation of methods to upgrade marginal mixtures. Interim Report II will document the laboratory evaluation and should be finalized in June 1994. Phase III will evaluate the concepts and techniques that have shown the greatest potential in the laboratory in field test sections. These test sections will be trafficked with aircraft loads and tire pressures to determine the performance of the marginal aggregates. The construction of the field test sections should be completed by April 1994, and trafficking should be concluded by August 1994. The final draft technical report will be submitted in September 1994.

REFERENCES

1. Gandhi, P. M. and Lytton, R. L. 1984. "Utility Decision Analysis to Select Aggregates for Asphalt Pavements," Transportation Research Record 989, Washington, DC.

2. Central Laboratory of France. 1981. "Use of Marginal Aggregates in Road Construction," Organization for Economic Co-operation and Development, Paris, France.

3. Rollings, R. S. 1988. "Substandard Materials for Pavement Construction," Miscellaneous Paper GL-88-30, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

4. Grau, R. W. 1979. "Utilization of Marginal Construction Materials for LOC," Technical Report GL-79-21, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

5. Elliot, R. P., Ford, M. C. Jr., Ghanim, M. and Tu, Y. F. 1991. "Effect of Aggregate Gradation Variation on Asphalt Concrete Mix Properties, " Transportation Research Record 1317, Washington, DC.

6. Marker, V. 1977. "Tender Mixes: The Causes and Prevention," The Asphalt Institute, Information Series Number 168.

7. Department of Commerce, 1962. "Aggregate Gradation for Highways, Simplification, Standardization, and Uniform Application and A New Graphical Evaluation Chart," Washington, D.C.

8. Moore, R. B. and Welke, R. A. 1979. "Effects of Fine Aggregate on Stability of Bituminous Mixes," Michigan Department of State Highways and Transportation, Research Report Number 78 TB-34-79F.

9. Brown, E. R. and Basset, C. E. 1990. "The Effects of Maximum Aggregate Size on Rutting Potential and Other Properties of Asphalt-Aggregate Mixtures, "Transportation Research Record 1259, Washington, DC.

10. Brown, E. R., McRae, J. L. and Crawley, A. B. 1989. "Effect of Aggregates on Performance of Bituminous Concrete," American Society of Testing and Materials STP 1016, Philadelphia, PA.

11. Herrin, M. and Goetz, W. H. 1954. "Effect of Aggregate Shape on Stability of Bituminous Mixes," Highway Research Board Proceedings.

12. Wedding, P. A., and Gaynor, R. D. 1961. "The Effects of Using Gravel as the Coarse and Fine Aggregate in Dense Graded Bituminous Mixtures," Proceedings AAPT, Vol 30.

13. Griffith, J. M., and Kallas, B. F. 1957. "Aggregate Voids Characteristics in Asphalt Paving Mixes," Highway Research Board Proceedings, Vol 36.

14. Griffith, J. M., and Kallas, B. F. 1958. "Influence of Fine Aggregates on Asphalt Concrete Paving Mixtures," Highway Research Board Proceedings, Vol 37.

15. Field, F. 1957. "The Effect of Percent Crushed Variation in Coarse Aggregates for Bituminous Mixes," Proceedings of the Association of Asphalt Paving Technologists, Volume 27.

16. Gaudette, B. E. and Welke, R. A. 1977. "Investigation of Crushed Aggregates for Bituminous Mixtures," Michigan Department of State Highways and Transportation, Research Report Number TB-58.

17. Maupin, G. W. Jr. 1970. "Effect of Particle Shape and Surface Texture on the Fatigue Behavior of Asphalt Concrete," Highway Research Record, Number 109.

18. Shklarsky, E. and Livneh, M. 1964. "The Use of Gravels for Bituminous Mixtures," Proceedings of the Association of Asphalt Paving Technologists, Volume 33.

19. Kalcheff, I. V. and Tunnicliff, D. G. 1982. "Effects of Crushed Stone Aggregate Size and Shape on Properties of Asphalt Concrete," Proceedings of the Association of Asphalt Paving Technologists, Volume 51.

20. Lottman, R. R. and Goetz, W. H. 1956. "Effect of Crushed-Gravel Fine Aggregate on the Strength of Asphalt Surfacing Mixtures," National Sand and Gravel Circular, Number 63.

21. Button, J. W. and Perdomo, D. 1990. "Influence of Aggregate Rutting in Asphalt Concrete Pavements," Transportation Research Record 1259, Washington, DC.

22. Kandhal, P.S. and Wenger, M. E. 1973. "Effect of Crushed Gravel Coarse Aggregate on Properties of Bituminous Concrete," Pennsylvania Department of Transportation, Research Project Report 70-28.

23. Ahlrich, R. C. 1991. "The Effects of Natural Sands on Asphalt Concrete Engineering Properties," Technical Report GL-91-3, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

24. Amirkhanian, S. N., Kaczmarek, D. and Burati, J. L. 1991. "The Effects of Los Angeles Abrasion Test Values on the Strength of Laboratory Marshall Specimens," Transportation Research Board, Washington, DC.

25. Dollar-Mantuani, L., 1978. "Soundness and Deleterious Substances," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, STP 169B, American Society for Testing and Materials, Philadelphia, Pennsylvania.

26. Brown, E. R. and Graham, R. T. 1985. "Potential for Using Loess in Sand Asphalt Mixtures," Miscellaneous Paper GL-85-23, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

27. Bootilier, O. D. 1967. "A Study of the Relation Between Particle Index of the Aggregate and the Properties of Bituminous Aggregate Mixtures," Proceedings of the Association of Asphalt Paving Technologists, Volume 36.

28. Huang, E. Y. 1962. "A Test for Evaluating the Geometric Characteristics of Coarse Aggregate Particles," American Society of Testing and Materials Proceedings, Volume 62, Philadelphia, PA.

29. McLeod, N. W. and Davidson, J. K. 1981. "Particle Index Evaluation of Aggregates for Paving Mixtures," Proceedings of the Association of Asphalt Paving Technologist, Volume 50.

30. Meir, W. R. and Elnicky, E. J. 1989. "Laboratory Evaluation of Shape and Surface Texture of Fine Aggregate for Asphalt Concrete," Transportation Research Board, Washington, DC.

31. Kandhal, P.S., Motter, J. B. and Khatri, M. A. 1991. "Evaluation of Particle Shape and Texture: Manufactured versus Natural Sands," Transportation Research Board, Washington, DC.

32. Winford, J. M. Jr. 1991. "Evaluation of Fine Aggregate Particle Shape and Texture and Its Effect on Permanent Deformation of Asphalt Paving Mixtures," Dissertation, Auburn University, Auburn, AL.

33. Marks, V. J., Monroe, R. W. and Adam, J. F. 1990. "The Effects of Crushed Particles in Asphalt Mixtures," Transportation Research Board, Washington, DC.

34. Foster, C. R. 1970. "Dominant Effect of Fine Aggregate on Strength of Dense-Graded Asphalt Mixes," Highway Research Board Special Report, Number 109.

35. Investigation of the Design and Control of Asphalt Paving Mixtures. 1948. Technical Memorandum No. 3-254, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

36. Cross, S. and Brown, R. 1992. "Effects of Aggregate Properties to Minimize Rutting of Heavy Duty Pavements," ASTM STP 1147, American Society for Testing and Materials, Philadelphia, PA.

37. Ahlrich, R. C. 1991. "Investigation of Airfield Pavement Failure at Cairo East Air Base," Miscellaneous Paper GL-91-20, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

38. Ahlrich, R. C. 1991. "Investigation of Airfield Runways at Jacksonville Naval Air Station," Miscellaneous Paper GL-91-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

39. Brown, E. R. 1983. "Asphalt Concrete Problems at Fort Rucker," Letter Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

40. Brown, E. R. 1983. "Investigation of Pavement Problem-Taxiway No. 1 at Castle Air Force Base," Letter Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

41. Anderton, G. L. 1990. "Evaluation of Asphalt Concrete Samples from O'Connel Boulevard-Fort Carson," Letter Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

42. Witczak, M. W. and J. Uzan, 1988. "The Universal Airport Pavement Design System; Report I of IV: Granular Material Characterization," Federal Aviation Administration, Washington, D.C.

43. Barksdale, R. D., 1991. *The Aggregate Handbook*, National Stone Association, Washington, D.C.

44. Nijboer, L. W., 1948. *Plasticity as a Factor in the Design of Dense Bituminous Road Carpets*, Elsevier Publishing Company, The Netherlands.

45. Yoder, E. J. and M. W. Witczak, 1975. *Principles of Pavement Design*, John Wiley and Sons, Inc., New York, New York.

46. Waterways Experiment Station, 1953. "Design of Upper Base Courses for High-Pressure Tires, Report No. 1: Base Course Requirements as Related to Contact Pressure" Technical Memorandum No. 3-373, Vicksburg, Mississippi.

47. Ahlvin, R. G., D. N. Brown, and D. M. Ladd, 1959. "Compaction Requirements for Soil Components of Flexible Airfield Pavements," Technical Report No. 3-529, USAE Waterways Experiment Station, Vicksburg, Mississippi.

48. Burns, C. D., 1962. "Total Thickness and Compaction Requirements for Flexible Pavements Subjected to Channelized Traffic," U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

49. Ahlvin, R. G., et al, 1971. "Multiple Wheel Heavy Gear Load Pavement Tests," Technical Report No. S-71-17, USAE Waterways Experiment Station, Vicksburg, Mississippi.

50. Yoder, E. J. and K. B. Woods, 1946. "Compaction and Strength Characteristics of Soil Aggregate Mixtures," *Proceedings*, Highway Research Board, Washington, D.C.

51. Ferguson, E. G., 1972. "Repetitive Triaxial Compression of Granular Base Course Material with Variable Fines Content," Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Iowa State University, Ames, Iowa.

52. Barksdale, R. D., 1973a. "Rutting of Pavement Materials," School of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia.

53. Casagrande, A. and W. L. Shannon, 1952. "Base Course Drainage for Airport Pavements," *Transactions*, Vol. 117, Paper No. 2516, American Society of Civil Engineers, New York, New York.

54. Cedergren, H. R. 1974. *Drainage of Highway and Airfield Pavements*, John Wiley and Sons, Inc., New York, New york.

55. Federal Highway Administration, 1980. "Highway Subdrainage Design," Report No. FHWA TS-80-224, Washington, D.C.

56. Barker, W. R., 1987. "Open-Graded Bases for Airfield Pavements," Miscellaneous Paper No. GL-87-16, USAE Waterways experiment Station, Vicksburg, Mississippi.

57. Nettles, E. H. and C. C. Calhoun, 1967. "Drainage Characteristics of Base Course Materials Laboratory Investigations," Technical Report No. 3-786, USAE Waterways Experiment Station, Vicksburg, Mississippi.

58. Atterberg, A., 1911. "Lerornas Förhallande Till Vatten, Deras Plasticitetsgränser och Plastiitetsgrader (The Behavior of Clays with Water, Their Limits of Plasticity and Their degrees of Plasticity)," *Kungligla Lantbruksakdemiens Handlingar och Tidskrift*, Vol. 50, No. 2, Sweden.

59. Rollings, R. S. and M. P. Rollings, 1992. "Pavement failures: Oversights, Omissions, and Wishful Thinking," *Journal of Performance of Constructed Facilities*, Vol. 5, No. 4, American Society of Civil Engineers, New York, New York.

60. Ahlvin, R. G., 1991. "Origin of Developments for Structural Design of Pavements," Technical Report No. GL-91-26, USAE Waterways Experiment Station, Vicksburg, Mississippi.

61. Barksdale, R. D., 1973b. "Laboratory Evaluation of Rutting in Base Course Materials," Proceedings, Third international Conference on the Structural Design of Asphalt Pavements, Vol. I, Ann Arbor, Michigan.

62. Chisolm, E. E. and F. C. Townsend, 1976. "Behavioral Characteristics of Gravelly Sand and Crushed Limestone for Pavement Design," Technical Report No. S-76-17, USAE Waterways Experiment Station, Vicksburg, Mississippi.

63. Haynes, J. H. and E. J. Yoder, 1963. "Effects of Repeated Loading on Gravel and Crushed Stone Base Course Material," Highway Research record No. 39, Highway Research Board, Washington, D.C.

64. Meininger, R. C., 1978. "Abrasion Resistance, Strength, Toughness, and Related Properties," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, STP 169B, American Society for Testing and Materials, Philadelphia, Pennsylvania.

65. West, T. R., R. B. Johnson, and N. M. Smith, 1970. "Tests for Evaluating Degradation of Base Course Aggregates," NCHRP Report No. 98, Highway Research Board, Washington, D.C.

66. Reidenour, D. R., E. G. Geiger, and R. H. Howe, 1976. "Suitability of Shale as a Construction Material," *Living with Marginal Aggregates*, STP 597, American Society for Testing and Materials, Philadelphia, Pennsylvania.

67. Kilvington, D. and G. Hamory, 1986. "The Performance of Natural Gravels as Base Course in Sealed Pavement," *Proceedings*, 13th Australian Road Research Board Conference, Vol. 13, Part 5, Melbourne, Australia.

68. Metcalf, J. B., 1988. "The Use of Naturally-Occurring Non-Standard Materials for Road Base Construction in Australia," 26th Australian Road Research Board Regional Symposium, Bunbury, Australia.

69. Fenwick, W. B., 1969. "Gyratory Compaction of Soil; Report 3: Crushed Limestone, Data Report," Technical Report No. S-68-6, USAE Waterways Experiment Station, Vicksburg, Mississippi.

70. Ray, M., 1986. "French Practice in the Stabilization of Road Pavements with Hydraulic Binders and in Surface Dressing," *Proceedings*, 13th Australian Road Research Board Conference, Vol. 13, Part 1, Melbourne, Australia.

71. "Stabicol: a Composite Material for Tomorrow's Roads," 1991. *Revue Générale des Routes et des Aerodromes*, No. 691, Paris France.

72. White, D. W., 1991. "Literature Review on Geotextiles to Improve Pavements for General Aviation Airports," Miscellaneous Paper No. GL-91-3, USAE Waterways Experiment Station, Vicksburg, Mississippi.

73. Webster, S. L. 1992. "Geogrid Reinforced Base Courses for Flexible Pavements for Light Aircraft," Federal Aviation Adminsitration, DOT/FAA/RD-92/25, Washington, DC.

74. Development of Gyratory Testing Machine and Procedures for Testing Bituminous Paving Mixtures. 1962. Technical Report 3-595, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

75. McRae, J. L. 1965. "Gyratory Testing Machine Technical Manual," Vicksburg, MS.

76. McRae, J. L. and Foster, C. R. 1959. "Theory and Application of a Gyratory Testing Machine for Hot-Mix Bituminous Pavement," Miscellaneous Paper 4-333, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

77. Department of Defense, MIL-STD-620A. 1966. Military Standard Test Methods of Bituminous Paving Materials, Washington, DC.

78. Pavement Mix Design Study for Very Heavy Gear Loads Pilot Test Section. 1962. Technical Report 3-594, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

79. Anderton, G. L. 1990. "Evaluation of Asphalt Binder Modifiers," Miscellaneous Paper GL-90-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

80. Al-Hussaini, M. M., and Townsend, F C. 1973. "Tensile Testing of Soils -- A Literature Review, Miscellaneous Paper S-73-24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

81. American Society of Testing and Materials. 1990. 1990 Annual Book of ASTM Standards, Vol 0403, Philadelphia, PA.

82. Brown, E. R. and Foo, K. Y. 1989. "Evaluation of Variability in Resilient Modulus Test Results" (ASTM D 4123), ASTM Journal of Testing and Evaluation, Philadelphia, PA.

83. Gabrielson, J. R. 1992. "Evaluation of Hot Mix Asphalt (HMA) Static Creep and Repeated Load Tests," Dissertation, Auburn University, Auburn, AL.

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